THE DESIGN AND DEVELOPMENT OF AN ELECTRIC DISCHARGE MACHINE WITH DIGITAL FEED BACK CONTROL

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CERTIFICATE

This is to certify that the thesis entitled, 'The Design and Development of an Electric Discharge Machine with Digital Feed Back Control' by Mr. Subhabrata Ghosal is a record of work carried out under our supervision and has not been submitted elsewhere for a degree.

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A C K N O W L E D G E M E N T S

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ABSTRACT

In the present work an Electric discharge machine employing Resistance Capacitance circuit for spark generation has been designed and developed. A new type of digital feed back control has been incorporated in the machine. Using a stepper motor-lead screw arrangement ,the incremental step wise movement of the tool has been obtained . The peak value of the spark waveform has been utilised to check whether the gap between the tool and the workpiece is within the preset gap width band. In case of any discrepency, the control automatically corrects the error. A theoretical analysis, based upon practical design constraints, has been carried out and optimal value of metal removal rate has been obtained in terms of electrical parameters of the R-C circuit. Without sacrificing high metal removal rate,precision, versatality of control and simplicity in design, the machine has been designed,and found to be much cheaper than the existing available models. Metal removal rates and Electrode wear rates for a combination of brass tool and mild steel workpiece have been measured. It has been observed that the performance of the machine is quite comparable with the existing commercial models.

CONTENTS

LIST OF FIGURES AND GRAPHS

NOMENCLATURE

V_B	=	Breakdown voltage
V_S	=	Supply voltage
T	=	Charging time
R	=	Resistance
C	=	Capacitance
E	=	Energy per spark
n	=	Frequency of sparking
I_s	=	Short circuit current
MRR	=	Metal removal rate
EWR	=	Electrode wear rate
WR	=	Wear ratio
x	= $\frac{V_B}{V_S}$ =	Non dimensional number
V_{ref}	=	Reference voltage
V	=	Voltage band
D	=	Diameter of pipe

CHAPTER I

INTRODUCTION

Machining of raw materials to obtain finished products has always played an important role in the whole history of human civilisation. Quantity of machined products for consumption has always been an important yard stick of the state of development of a society.

Machining can be broadly described as the removal of excess amount of material to obtain a desired product of particular shape, size and finish. In conventional machining processes, mechanical energy is used to do the above conversion. Here the tool having one or more sharp cutting edges is made to rub against the workpiece. There is always a relative motion between them and by maintaining a controlled interaction (feed and depth of cut), the excess amount of material is removed. In conventional machining , the excess amount of material is removed in the form of chips which are produced by plastic deformation of the job material at the tool -job interacting face. Thus in conventional machining, the cutting edges of the tool must be always harder than the workpiece so that material is removed only from the workpice and not from the tool.

1.2 Unconventional Maching Processes:

The rapid advance of science and technology from 1930 has imposed severa restriction on the concept of conventional machining. There had been a tremendous spurt in the discovery of new materials and alloys having high strength and temperature resistance characteristics, because of the demands from aerospace and nuclear engineering. Since in conventional machining process, tool is always harder than workpiece ,it has become more and more difficult to machine the above types of materials. Thus it has become essential to develop new cutting tool materials as well as processes which can safely and efficiently machine these new materials with high productivity and high accuracy. The newer techniques of machining has effectively solved the problems imposed by the increasing demand for high-strength temperature-resistant alloys, the requirement of parts with intricate and complicated shapes and sizes of high accuracy which are practically impossible to achieve by conventional machining processes. All these processes have been grouped under the common heading-''Unconventional Machining Processes''.

1.3 Classification of Unconventional Machining Processes:

The unconventional machining processes can be classified according to the type of energy required, which are as follows:

(i) Mechanical: Here the material removal takes place by mechanical erosion process. Abrasive jet machining uses a focussed stream of fluid with abrasive particles. In Ultrasonic machining,material is removed by brittle fracture caused by repetitive impacts of small abrasive grains on the work surface at high frequency. In water jet machining high pressure high velocity water jet is made to strike the workpiece to remove the material.

(ii) Electrochemical: Here the metal is removed by ion displacement with some electrolyte as media. In Electro-chemical machining this is achieved by anodic dissolution of the positively charged workpice seperated from a suitably shaped negatively charged tool by a thin film of flowing electrolyte. In electro-chemical grinding metal removal is achieved from a conducting positive workpiece by rotating a conductive abrasive wheel serving as a cathode with a thin film of flowing electrolyte between them.

(iii) Chemical: Here the material is removed by the ablative action under the action of a chemically reactive agent.Chemical machining is a process of controlled dissolution of material in contact with strong chemical reagent. In chemical etching or chemical milling material is removed by an etchant solution which is sprayed over the zone of machining or the workpiece is dipped in the solution with thh portions not to be machined protected by a suitable coating

of etchant resistance material. Hot chlorine machining is a gaseous form of chemical machining by a reactive gas like chlorine.

(iv) Thermoelectric: Here the material is removed by vaporisation and/or fusion. In Electron beam machining a focussed stream of high velocity electrons hits the work surface. The kinetic energy of the moving electrons is converted into heat causing melting and vaporisation of the workpiece material at the point of impact. In Laser beam machining, material is removed by a focussed mono-frequency collimated light beam which melts and vaporises the workpiec material at the focussed area. In Plasma arc machining a gas like H_2, N_2 etc is heated by an arc to a high temperature to become partially ionised. This ionised stream of gas is impinged on the worksurface to cause it to melt and erode. Finally in Electric discharge machining metal is removed from a conductive workpiece by a rapid repetitive spark discharge initiated between the negatively charged tool and positively charged workpiece separated by a flowing dielectric fluid.

1.4 Electric Discharge Machining (EDM) Process :

In this unconventional machining process, material removal is obtained by passing a number of electrical sparks in rapid succession between the tool (cathode) and workpiece (anode) kept immersed in a dielectric fluid and separated by a controlled gap. A controlled erosion of material from the workpiece can be obtained by suitably

controlling the various electrical parameters and the gap between the tool and the workpiece.

The electric discharge or the spark is obtained by making a sufficiently high potential difference between the tool and workpiece, which is adequate for the break down of the dielectric medium. The ionised dielectric, becomes a conducting path and allows the current to pass. The fluid becomes again deionised in a very short time after the discharge.

By suitable circuits, the above process of sparking between the tool and the workpiece can be repeated from tens of thousands to millions per second.

1.5 Material Removal by EDM:

Of the several theories put forward attempting to explain the mechanism of material removal, the following has been accepted as the most suitable one. However, no theory can explain the complicated phenomenon perfectly.

Fig. 1.1 shows tool and workpiece connected to the negative and positive terminals of a D.C. supply. Let the potential difference between the electrodes be gradually increased from zero. No current would flow until the potential difference reaches the breakdown voltage corresponding to the gap between the electrodes. When this voltage is reached, breakdown of the dielectric takes place and allows a current to flow between the tool and the workpiece in the form of a spark. In order to explain the erosion, one has to make the microscopic study of the tool

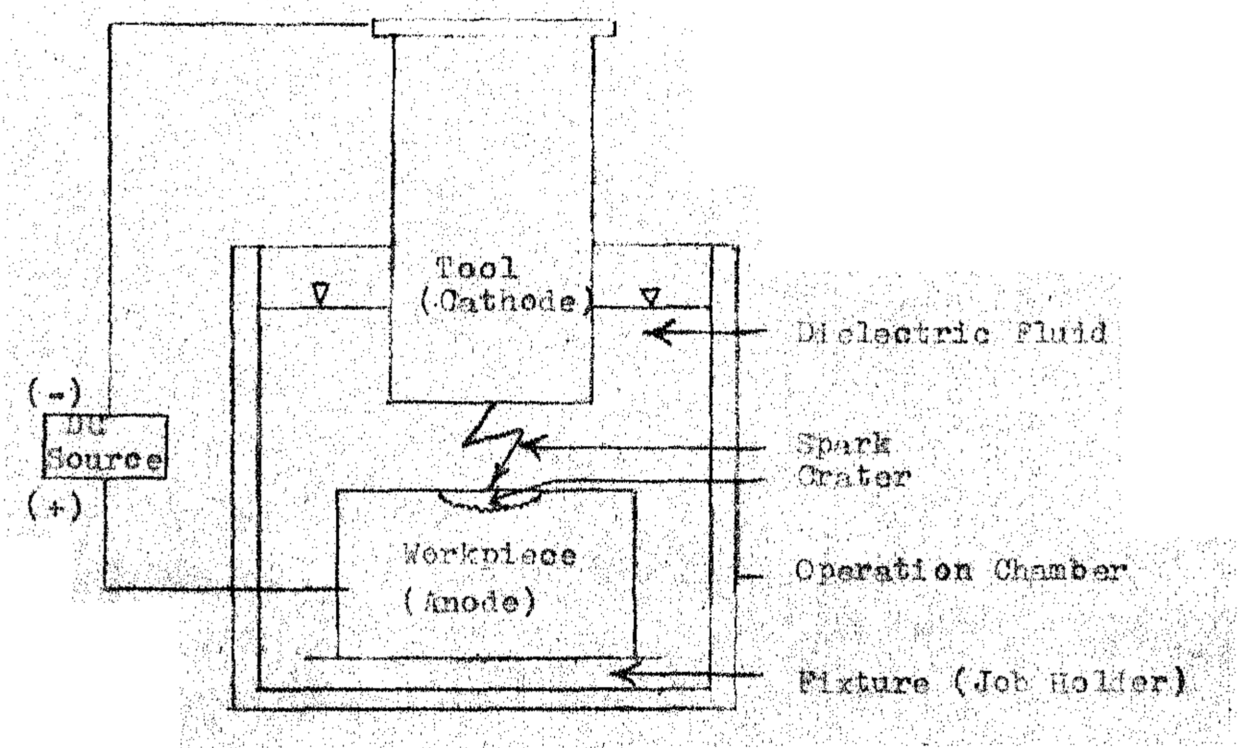


Fig. 1.1 Basic Scheme of EDM Process

and the workpiece surfaces. No matter how smooth the surfaces may look, due to surface roughness there will be peaks and valleys if viewed microscopically. So when two such surfaces approach each other, there will be one unique point where the spark will take place, because the distance between these two points is minimum. As soon as a spark takes place, some amount of material will be eroded resulting in the increase of distance from the previous state. The next spark will take place again between such two points where the distance is least, causing further removal of material. Thus the spark will go on shifting from one point to the other and will eventually move all over the tool and corresponding work-piece surface.

The release of energy from such a spark will result in a local increase of temperature reaching thousands of degrees and also causes a deformation in the top layer of both tool and workpiece surfaces. A part of the metal is removed by direct evaporation and some amount of metal is thrown out of the parent body causing a crater to be formed in the electrode surface. The heat is dissipated in the surrounding dielectric fluid medium and the particles formed are removed along with the dielectric fluid. This process is repeated again and again and an exact replica of the tool shape is formed on the workpiece. The tool also undergoes erosion simultaneously. By selecting proper electrical parameters the electrode wear rate (EWR) or tool wear rate can be substantially reduced.

1.6 Applications of EDM.

The Electro discharge machining process differs from the traditional processes as follows:

1. There is no direct contact between the tool and workpiece. Hence there is no transmission of force.
2. The tool need not be harder than the workpiece. The tool electrode is normally made from cast iron, brass, copper, graphite, copper-tungsten etc.
3. Only one electrode can be used to obtain a continuous range of surface finish , from very rough to very fine, simply by changing parameters of the electrical circuits.
4. All materials including very tough and brittle ones can be very easily machined.
5. Since tool shape is eroded into workpiece, any type of intricately shaped holes and unusual and difficult geometry can be obtained very easily.
6. Very fine and accurate holes can be easily drilled with great accuracy and ease.

For the above reasons, EDM is widely used in tool rooms for the production of dies and punches. Delicate workpieces that are not strong enough to support the cutting force can be machined by EDM. The disadvantage of lower material removal rate is easily offset by its other advantages. Apparently, from economic point of view EDM may seem to be costly but Ashby [1] has shown the justification

of EDM from purely economic point of view considering over all cost of production.

1.7 Objective and Scope of the Present Work :

Although Electric discharge machines are widely used abroad as well as in the country for commercial purposes, it has been observed that the development of indigenous know-how needed for the manufacture of these machines is not very significant. Machines available in the country are based upon conventional design. As a result, the cost of such machines is very high and beyond the reach of small industries. The major objective of the present work is to design and develop a new EDM system at a low cost without sacrificing precision, simplicity in design, versatility of control and high material removal rate. Based on these guidelines, it was decided to employ the RC (relaxation) circuit, incorporating a complete digital feed-back control for the tool movement using the spark wave-form itself to implement the feed-back control. The scope of the present work includes an analysis of the RC circuit under certain assumptions based on practical design constraints, as well as a study of the frequency pattern, MRR, EWR and Wear ratio for different values of supply voltage, resistance and capacitance, in order to test its commercial worthiness.

CHAPTER II

A REVIEW OF THE EDM PROCESS

As explained in the earlier chapter, this process removes material from the workpiece through repetitive sparking between a controlled gap within a dielectric medium . This had been observed by Russian Scientists N.I.
m
Lazarenko and B.R.Lazrenko in 1943. They had used an R-C or relaxation type of circuit. The operation of this is explained below.

2.1 Resistance-Capacitance Circuit (Relaxation Circuit)

Fig. 2.1 gives a schematic diagram of the above circuit. The capacitance C is charged through a resistance R from a D.C. supply voltage V_s till it reaches the break-down voltage V_B corresponding to the gap between the tool and the workpiece. It discharges through the gap and a small amount of material is removed from the workpiece.Right after the discharge, current starts charging the capacitance again, thus repeating the process again and again. The voltage waveform across the gap is shown in Fig. 2.2. The time of charging is dependent upon the values of V_s, V_B, R and C, governed by the following equation:

$$V_B = V_s \left(1 - e^{-\frac{T}{RC}} \right) \qquad (2.1)$$

where V_B = Break down voltage

V_s = Supply voltage

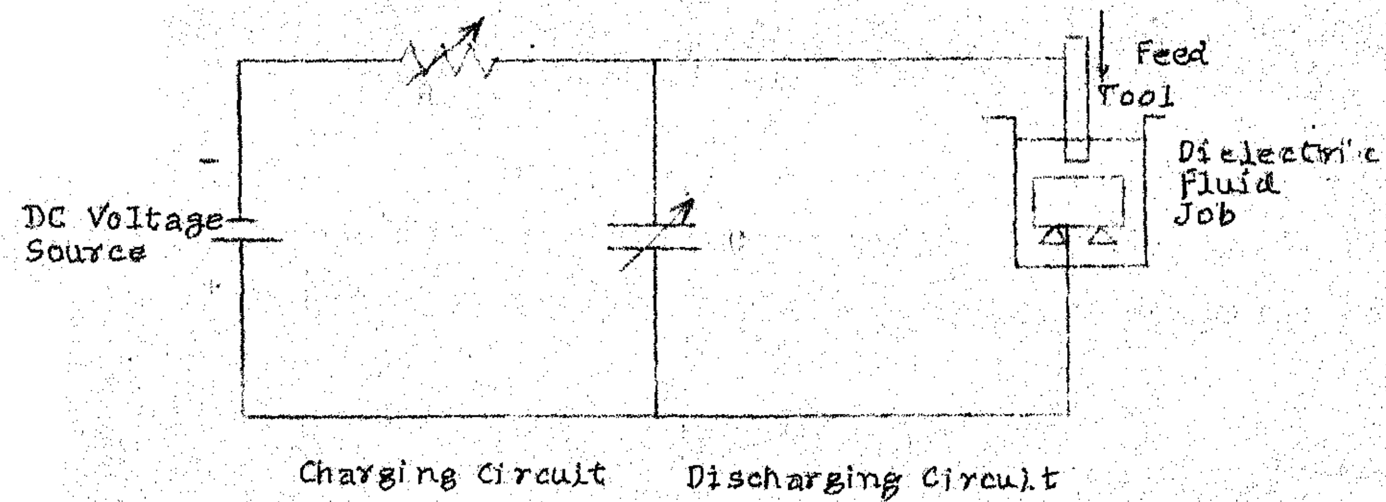


Fig. 2.1 Schematic Diagram of Resistance-Capacitance Circuit

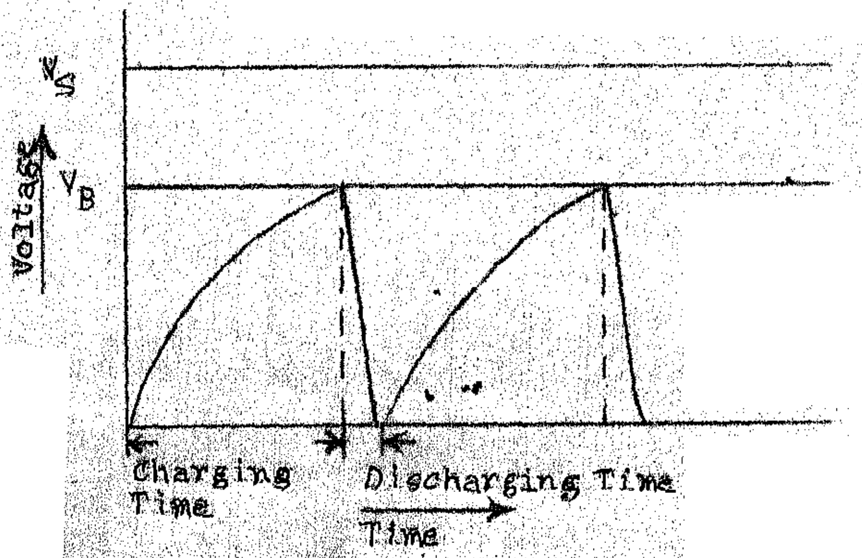


Fig. 2.2 Voltage Waveform in Relaxation Circuit

T = Charging time in seconds.

R = Resistance in ohms.

C = Capacitance in farads.

In actual practise, the value of V_B fluctuates from one spark to another and the waveform shown in Fig. 2.2, is not really periodic having a fixed frequency for any given setting of V_s, R and C. The average number of sparks taking place per second, which is of interest to us for a quantitative evaluation of the process will henceforth be referred to as the ''Frequency of Sparking'', denoted by n. Had the sparking been exactly periodic, n would have been given by the reciprocal of T, neglecting the discharge time, which is always extremely small in comparison with T.

In relaxation circuits, the metal removal rate (MRR) depends upon the energy per spark and the frequency of sparking. The following expression of MRR is given by Lazarenko and Lazarenko [2].

$$MRR = K.E.n. \qquad (2.2)$$

where K is a constant depending upon physical properties of electrode materials, dielectric fluid and duration of pulse, and E is the energy per spark given by the following expression:

$$E = \frac{1}{2}\, C.\, V_B^2 \qquad (2.3)$$

where, E = Energy per spark.

C = Capacitance value

V_B = Breakdown voltage

A detailed analysis of the MRR obtainable from the R-C circuit, based on practical design limitations, is given in the next chapter.

The above expressions show the dependance of MRR on various parameters. So in order to achieve a high MRR, a judicious selection of various controlling parameters are to be made.

2.2 EDM Development :

The electric discharge machine can be described as a machine which employs EDM process to produce intricate and unusual geometrical parts with sufficient accuracy and high degree of surface finish. From mid 1950 onwards there had been a tremendous spurt towards commercial utilisation of the above process, once its immense potential was realised. This resulted in advances, through research, in various directions. The major studies are concerned with the following aspects.

1. Supply circuits for spark generation.
2. Spark gap controlling mechanism.
3. Tool Electrode material .
4. Design of machine, adoption for machining various surfaces, tooling etc.

2.2.1 Spark Generation Circuits.

The R-C circuit has already been briefly discussed in the previous section. One of the major limitations of the R-C circuit arises from the fact that there is a minimum possible value of the resistance that can be used. A lower

resistanse leads to arcing and hence a poor surface finish [3] . This rostricts the maximum frequency obtainable from this type of circuit to 10-12 KHz [4].

To over-come these inherent difficulties, many other types of spark generating circuits have been developed [5] . These generators can produce sparks at very high frequency in the order of megacycles and of high energy. Many typical circuits have been shown in reference [5]. However, the R-C circuit is still widely used for the following advantages:

i) Simplicity of construction.

ii) High metal removal rate.

iii) Ruggedness.

iv) Reliability.

v) Low cost.

2.2.2 Spark gap controlling Mechanism:

This is one of the most important factors for efficient operation. Since material is removed from workpiece with each spark, the gap increases requiring higher break-down voltage. This in turn, reduces the frequency, unless the gap is reduced. This is shown in Fig. 2.3 considering a R-C circuit. Thus, to maintain high MRR, accurate gap control is absolutely essential.

This has been tried by a number of researchers. A controller patented in Switzerland [6] uses hydraulic pressure to control the gap with a delay of 4 μ sec. A suggestion from Japan [6] is based on two stage feed drive

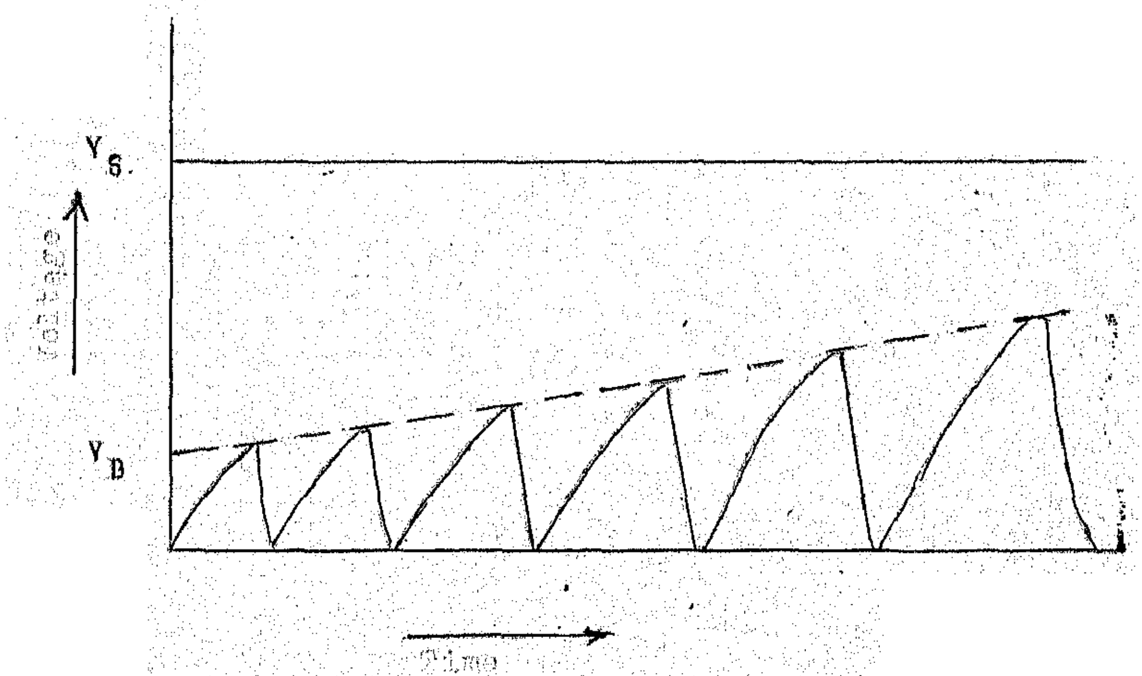


Fig. 2.3 Spark Voltage Waveform with Stationary Tool

to tool. *Another suggestion from U.K.* [6] involves feeding of tool to the workpiece by a d.c. motor through a reduction gear. An electromagnetic control reported [7] was fabricated and applied in this Institute [8]. However, servo control has been found to be most widely used in commercial machines [1]. In most of the cases either a servo-amplifier circuit is used where voltage difference is amplified before being fed to d.c. servo motor or by an electro hydraulic system where the error voltage is fed to an electro hydraulic servo valve which in turn feeds an hydraulic cylinder to move electrodes up and down [1]. A type of electronic control is used by a manufacturing company [9] , details of which are lacking. Russian machines [10] have been found to use servo motor for the gap control. In most of the commercial machines and publications, however, the details of gap control mechanism are not given.

2.2.3 Tool Electrode Material:

The factors to be considered in deciding the electrode material are

i) the ability to produce the required shape.

ii) the number of cuts that can be made within an acceptable tolerance.

iii) Minimum tool wear.

Copper, tungsten and graphite alloys have been proved to be very effective and wear rate under various conditions have been reported [11, 12]. Tungsten carbide tipped

and Elkonite (copper-tungsten /silver-tungsten) tipped tool have been reported to be used to minimise cost [13]. It has been found that tool wear can be reduced by connecting an additional inductance and resistance in the sparking circuit or using a weak dielectric fluid [4,14].

2.2.4 Development in the Design of Machines:

Machines have been put into commercial use since mid 1950's . Machines have been designed having special types of chucks to hold any shape and size of tool [10]. Movement in all three direction of the tool as well as holding at a fixed angle is quite common at present [10,19]. Present day machines are capable of handling workpieces weighing upto 10 tons [10]. Czechoslovakian spark erosion machine reported as early as 1956 [15] was capable of making holes of diameter 0.020'' to 0.0020''. Reports about G.K.N. spark erosion machine built in 1958 [16] are available . Lockheed Air corporation has used EDM for finishihg the cavities of impact extrusiondies after hardening in 1958 [17]. Details of some later models (1968) are available with high tolerance alongwith various complicated operations performed on it. Data about a number of Russian models are also available [10]. A couple of special features like servo-feed work table and pulsed injection of dielectric liquid synchronised to electrode pulsation, are available with Charmilles and Agietron group of EDM

machines [18]. There are special types of machines which have the tool movement from the bottom to the top (inverted tool) and the tool being given a rotational motion during machining process [17]. Some special purpose machines have been designed and used commercially to meet special requirements i.e. to make 0.0020 inch dia holes [20] or production of very complicated contours [21].

CHAPTER III

DESIGN CONSIDERATIONS

The design of the whole system has been based on two important considerations, simplicity of construction and low cost of production, without sacrificing the essential details, listed below:

i) High precision of all moving parts of the machine.

ii) High accuracy of tool position control and indicating mechanisms.

iii) Reliability of operation.

iv) Provisions for rapid removal of erosion products from machining zone.

v) Efficient filtering of dielectric fluid.

vi) Highest possible degree of automation.

vii) Provisions for adjusting the electrical parameters over wide ranges.

viii) Provision for mounting workpieces of various shapes and sizes.

ix) Provision for fixing electrodes of various shapes and sizes.

x) High rigidity in design.

xi) High material removal rate.

3.1 Optimisation of MRR:

One of the most important performance criteria which determine the commercial worthiness of an Electric discharge machine is the maximum MRR attainable from it . A theoritical analysis of the MRR obtained with the R-C circuit is given below which relates MRR with the electrical parameters V_s, V_B, R and C and obtains the optimum value of V_B for a fixed supply voltage for maximum MRR.

Equation 2.2 gives an expression for MRR in terms of energy per spark and frequency of sparking. Substituting E from equation 2.3,MRR can be expressed as follows

$$MRR = \frac{1}{2} KC V_B^2 n \qquad (3.1)$$

Thus optimum values of V_B and n are to be found out in terms of the fixed parameters V_s,R and C so that for this given setting highest MRR is obtained,

The fixing up of the values of V_B and n poses a new problem. The phenomenon of sparking is highly stochastic in nature and values of V_B and T do not remain constant during the EDM process. This is a consequence of random fluctuations in the width of the gap across which the sparking takes place. The study of the randomness of V_B and T is beyond the scope of the present work. In order to proceed with the analysis, therefore, a more general expression for MRR under non-uniform sparking is first derived, and a generalised interpretation of equation 3.1 is given as follows.

Let T_1, T_2, -------, T_i, --------T_m be the time periods of m consequetive sparks corresponding to breakdown voltages V_{B_1} V_{B_2}, ------, V_{B_i} ------ V_{B_m} . The amount of material removed by the i^{th} spark is given by

$$M_i = \tfrac{1}{2} KC V_{B_i}^2 \tag{3.2}$$

The total amount of material removed by m sparks is thus given by $\sum_{i=1}^{m} M_i$

$$\text{Therefore,} \quad MRR = \frac{\sum_{i=1}^{m} M_i}{\sum_{i=1}^{m} T_i} = \frac{\tfrac{1}{2} KC \sum_{i=1}^{m} V_{B_i}^2}{\sum_{i=1}^{m} T_i} \tag{3.3}$$

Comparision of equations 3.1 and 3.2 immediately yield the following results:

$$\frac{1}{n} = T \equiv \frac{1}{m} \sum_{i=1}^{m} T_i$$

$$\text{and} \quad V_B^2 \equiv \frac{1}{m} \sum_{i=1}^{m} V_{B_i}^2 \tag{3.4}$$

In all future considerations, therefore, V_B will denote the r.m.s. value of the actual breakdown voltages encountered in a sequence of sparks.

It can be shown (vide Appendix A) that, for sufficiently small fluctuations in the gap width, resulting in corresponding variations in the break down voltage and time of charging , V_B and T satisfy equation 2.1.

Equation 2.1 can be written in-terms of n as follows.

$$V_B = V_s \left(1 - e^{-\frac{1}{nRC}} \right)$$

or

$$n = \frac{1}{RC \ln \frac{V_s}{V_s - V_B}} \qquad (3.5)$$

From equations 3.1 and 3.5 , after simplification, the following exprression for MRR is obtained.

$$MRR = \frac{K}{2} \frac{V_B^2}{R \ln \frac{V_s}{V_s - V_B}} \qquad (3.6)$$

Certain fundamental observations can be made from the above equation.

i) MRR is independent of the value of the capacitance used. It only depends upon V_s, V_B and R.

ii) MRR is inversely proportional to R for a given setting of V_s and V_B. A decrease in the value of R, with V_s and V_B unchanged, will cause a corresponding increase in MRR. However, as explained in section 2.2.1, the value of R can not be lowered beyond a certain minimum value. Over and above the restriction due to arcing, the lower limit on the value of R is further restricted due to current-handling capacity of individual electrical parts and components used in the machine. If the maximum current that a machine can handle is I_s the minimum value of R that can be used for a given choice of V_s is given by

$$R_s = \frac{V_s}{I_s} \tag{3.7}$$

This ensures that the current handling capacity is not exceeded even under short circuit condition. Hence, subject to the lower limit R_{min} required to prevent arcing, maximum MRR is always obtained if R is chosen equal to R_s as given by equation 3.7 for any choice of V_s. Under this condition, which will henceforth be referred to as the ''Constant short-circuit current'' condition,

$$MRR = K' \frac{V_B^2}{-V_s \ln (1 - \frac{V_B}{V_s})} \tag{3.8}$$

MRR is thus dependent on only two parameters: V_s and V_B. The maximum value of MRR for a given V_s can be obtained by differentiating equation 3.8 with respect to V_B and then equating it to zero. This yields the condition.

$$\frac{V_B}{V_s - V_B} = -2 \ln \left(1 - \frac{V_B}{V_s} \right) \tag{3.9}$$

This may be written in form

$$\frac{x}{1-x} = -2 \ln (1 - x) \tag{3.10}$$

$$\text{where } x = \frac{V_B}{V_s} \tag{3.11}$$

The equation 3.10 is a transcedental equation and its only non-trivial root is

$$x = 0.7145 \quad (3.12)$$

or $$V_B = 0.7145\ V_s \quad (3.13)$$

Thus for a given value of V_s, V_B should be set at 71.45 % of V_s, in order to get maximum MRR.

Figure 3.1 shows the variation of MRR with respect to V_B for different values of V_s. It is clear from the curves that MRR is a monotone increasing function of V_s for constant V_B, the rate of increase decreasing monotonically to zero. This can be easily verified by differentiating equation 3.8 with respect to V_s and then equating it to zero. This yields the following transcedental equation

$$\frac{x}{1-x} = -\ln(1-x) \quad (3.14)$$

which has no root except $x=0$ and $x = 1$, which are trivial solutions . The following conclusions can be drawn from the for going analysis.

A) For any given choice of V_s, the maximum MRR is obtained for a value of V_B nearly equal to 70 percent of V_s. An added advantage of operating in the neighbourheod of the optimal value of V_B is that MRR is essentially unaffected even if V_B fluctuates as much as $\pm$ 15 percent.

B) Referring to equations 3.2 and 3.8 , it becomes evident that a decrease in C leads to an improvement in the surface finish without affecting MRR. This happens due to the decrease in M_i. Nothing is conclusively known about the minimum permissible value of C, which, hence has to be

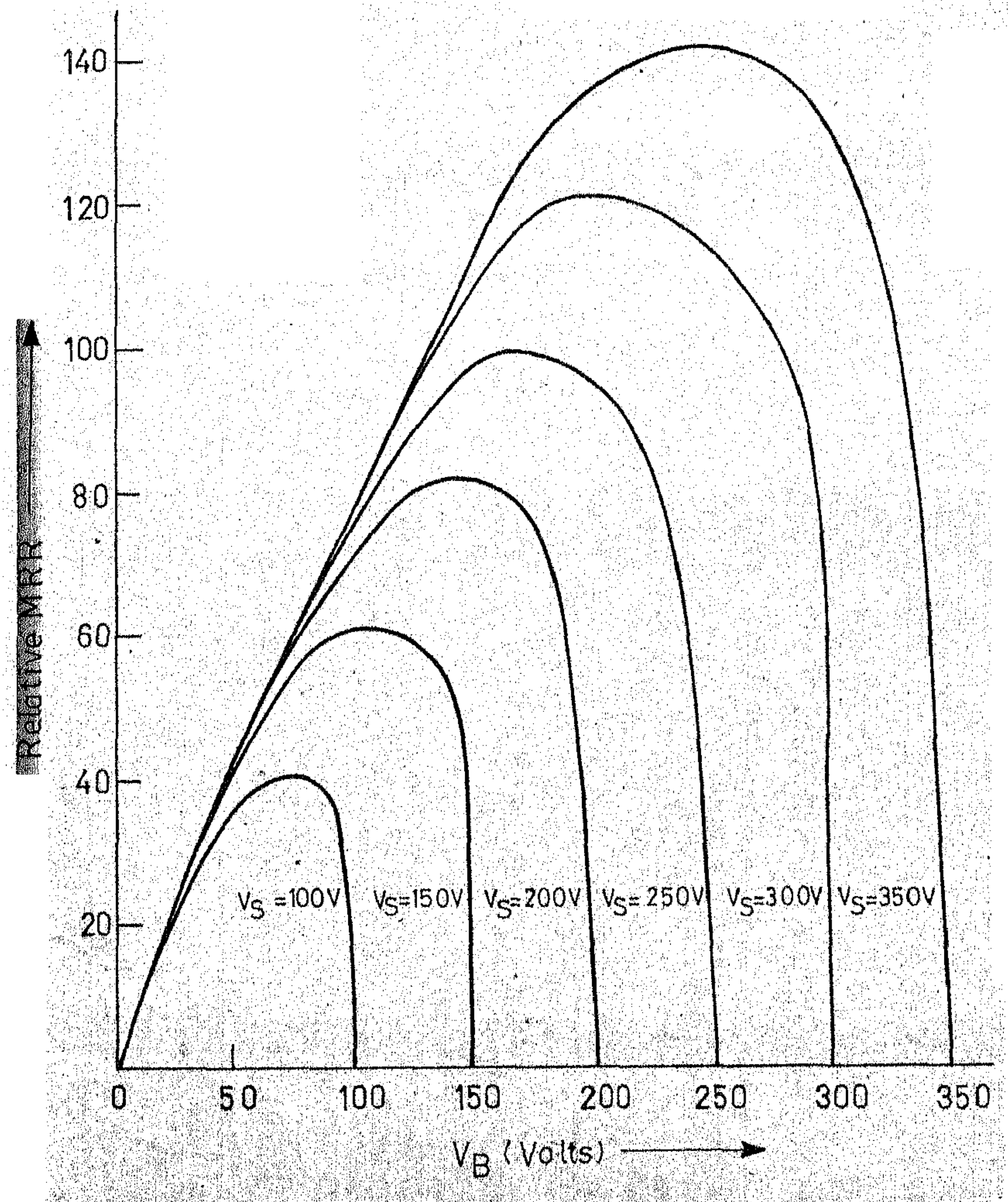


Fig.3.1 Variation of MRR with break-down voltage

found out experimentally.

C) In case, even the minimum permissible C is not capable of giving the desired surface finish because of high values of V_B and hence V_s, the value of V_B has to be lowered. This can be achieved only at the cost of MRR. There are two options at this stage.

a) V_s can be kept high leading to operation away from the peak point of the curve.

b) V_s can also be correspondingly lowered so that the operation is again in the neighbourhood of the peak point of a different curve. Although the first choice would give a higher MRR than the second choice, the latter is preferrable for the following reasons.

i) The advantage of operating in the neighbourhood of the optimum point as mentioned before is retained.

ii) Since R has to be reduced alongwith V_s to maintain the same ''Constant short-circuit current'' condition, the power drawn from the DC supply will be automatically reduced.

iii) The difference in the MRRs obtained in the two cases mentioned in (i) and (ii) above for any given V_B, is never too high to offset the foregoing advantages.

Keeping in mind the random spark to-spark variation in the breakdown voltage, it is never possible to exactly set V_B at the desired optimal value. The design has

therefore, to provide for a prescribed band of voltage which would contain the optimal choice of value of V_B, thus ensuring that the process always operates under nearly optimal operating condition.

3.2 Control Features for Optimal Spark Generation:

To implement as well as test the ideas that have come out from the analysis carried out in the previous section, sufficient flexibility should be provided in the spark generating circuit so as to permit a wide range for each of the circuit parameters. The desirable features are listed as follows.

i) There should be an arrangement for continuous adjustment of V_s. This can be easily obtained by varying the AC input to the rectifier used to generate DC, by employing a Variac.

ii) Corresponding to each value of V_s, set by means of variac, it should be possible to have an appropriate value of the resistance R, so that the ''Constant short - circuit current'' condition can always be maintained. This can easily be done by using a Rheostat in the circuit.

iii) For obtaining various types of surface finish, a control on the selection of different values of capacitance should be available. Since continuous variation of a high capacitance is not feasible, the best one can do is to employ a selector switch which would put different values of capacitance in the circuit as needed.

3.3 Requirements of the Tool Control System.

As already decided, the actual up and down movement of the tool is to be obtained by means of a stepper motor-lead screw arrangement. The whole tool control thus reduces to the control of the number of steps and the direction of rotation of the stepper motor. The following features are necessary to maintain versatile control of the movement.

The tool control system should have two different controlling modes, automatic or manual. In the automatic mode, the tool position should adjust itself so as to maintain a constant break down voltage V_B, (rms value), as set by a continuously variable command voltage. This requires a negative feed-back control system which would sense the error between the preset value V_B and the instanteneous value V_{B_i} corresponding to any particular spark, and would generate signals for driving the stepper motor in the proper direction. In the manual mode, on the other hand, the operator should have full choice to move the tool, up or down, as desired, by any number of steps.

It would be convenient to have two kinds of motion under manual control from the point of view of fast as well as precise adjustment -(i) a continuous jogging motion as long as the manual command is on and (ii) a single step movement every time a manual command is given. Moreover to facilitate quick rising of the tool for the purpose of

flushing etc, a provision should also be made to enable the tool to be moved faster than the normal operating speed.

Following interlocking are also desirable.

i) The automatic mode must override any manual command.

ii) Up and down as well as jog and step commands must be mutually exclusive.

Based upon the above requirements, the whole tool control circuit is designed and the realisation of the actual circuitry to meet the above requirements is discussed in the next chapter.

3.4 Mechanical Design Features:

In the mechanical design of the machine, the following points are taken into consideration:

i) Vertical movements of the tool with sufficient accuracy and precision.

ii) Control arrangement for positioning the working basin.

iii) Recirculation of dielectric fluid with filtering unit.

The total length of travel for the tool is restricted to 15 cm and the least count of the linear movement shall be of the order of 1.25 thousands of a cm. To obtain digital control over tool movement, a stepper motor is used. In such a motor, by systematic energisation of the different coils of the motor, the output shaft can be made to rotate in steps in both direction. In Appendix B, the motion of a stepper

motor has been discussed.

In order to convert the rotational motion to a linear motion, the output shaft is rigidly coupled to a lead screw passing through a nut fixed to the tool holding system. A dovetail guide is provided to maintain the required precision.

To obtain the necessary least count of the linear movement, a stepper motor having 200 steps per rotation is selected. Its output shaft, when connected to a lead screw of pitch 3.2 mm in the manner described earlier, gives the least value of linear movement equal to 1.7×10^{-3} cm which is quite comparable to the desired one.

Figure 3.2 shows schematically the recirculation system. For recirculation, the suction line of a pump is connected to the tank and its delivery is returned to basin. A bigger diameter pipe return the fluid to the tank. The actual diameter of the pipes needed have been calculated based on available pump capacity and the position of connections of pipes in the tank. The calculations are shown in Appendix C.

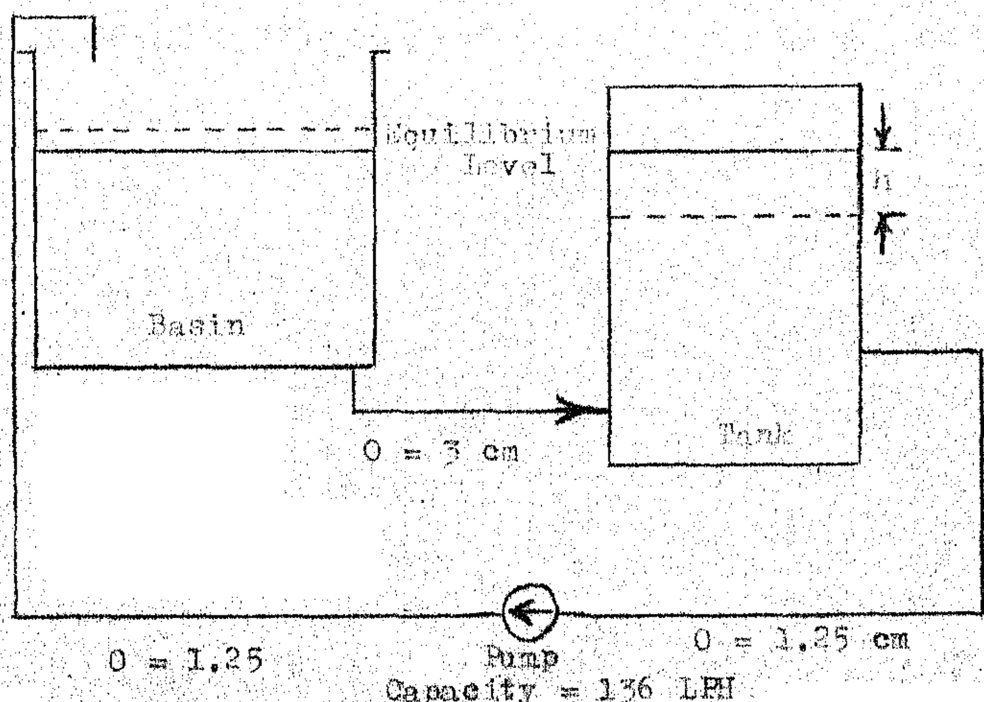


Fig. 3.2 Schematic Diagram of Recirculation System

CHAPTER IV

ELECTRICAL AND ELECTRONIC CIRCUITRY

In this chapter the actual spark generation circuitry along with tool control principles and circuitry development have been discussed. The whole circuitry have been divided into two sections: the Spark generation circuitry which has been termed as Electrical circuits and Digital tool control circuitry termed as Electronic circuits. Special features of digital tool control system have also been discussed.

4.1 Electrical Circuits:

As already mentioned, this deals exclusively with spark generation circuit, the basic principles of which have already been explained in chapter II. The block diagram is shown in Fig. 4.1 and the actual realisation is schematically shown in Fig. 4.2.

The main AC power supply goes to a variac, and the output is passed through a full wave rectifier to obtain DC voltage. This is followed by a capacitance acting as a filter capacitance which smoothens the rectified voltage and a steady DC voltage is obtained. This is followed by a rheostat and a capacitor bank, providing R and C respectively. By postioning the slider, any value of resistance from 0 to 100 ohms can be obtained. A selector switch chooses 4

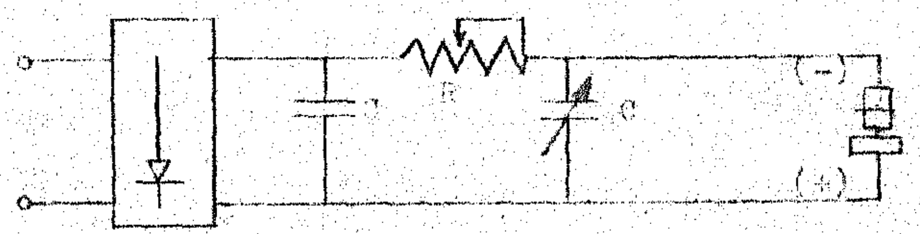


Fig. 4.1 Block Diagram of Spark Generation Circuit

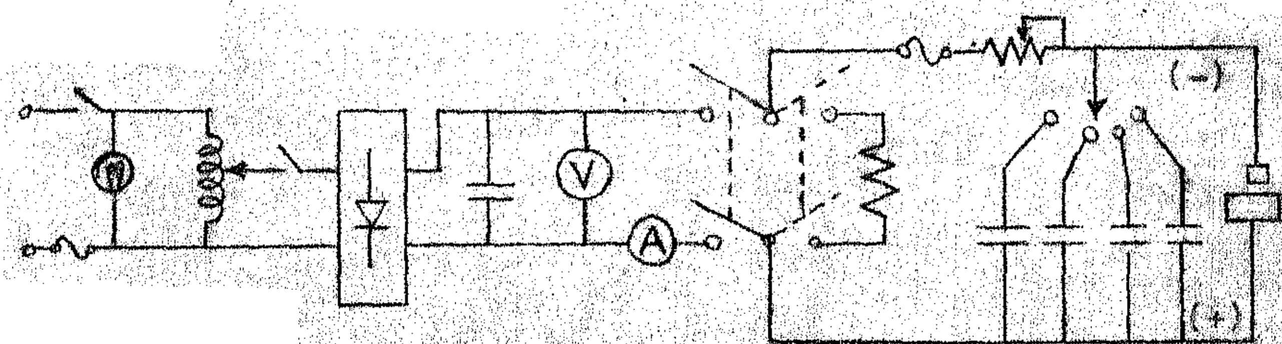


Fig. 4.2 Schematic Diagram of Actual Circuit Used

different values of capacitance, the lay out of which is shown in Fig. 4.3. The positive side of this is connected to the workpiece where as negative side is connected to the tool.

4.2 Electronic Circuitry:

A digital electronic tool control has been made for accurate gap setting between the tool and workpiece. Here, instead of existing electro-hydraulic servo system, which is very costly, a servo system based an incremental drive has been designed and used. This type of drive has been achieved by using a stepper motor, the basic property of which makes digital control of tool movement possible.

4.2.1 Principle of Control:

Depending upon the gap between the workpiece and the tool, the break down voltage is determined and the stored energy of the capacitance is discharged in the form of a spark. In case of too large a gap the deelectric break-down never occurs and in case of too small a gap, sparking is replaced by arcing which is very undesirable from machining point of view. Other than these two extreme cases, the following 3 possibilities can occur which are shown in Fig. 4.4.

As already mentioned in chapter II MRR and quality of surface finish depend on the frequency of sparking and energy per spark. Both of these are dependent upon the peak value of the break down voltage as shown earlier. Thus for high MRR and surface finish V_B need to be controlled

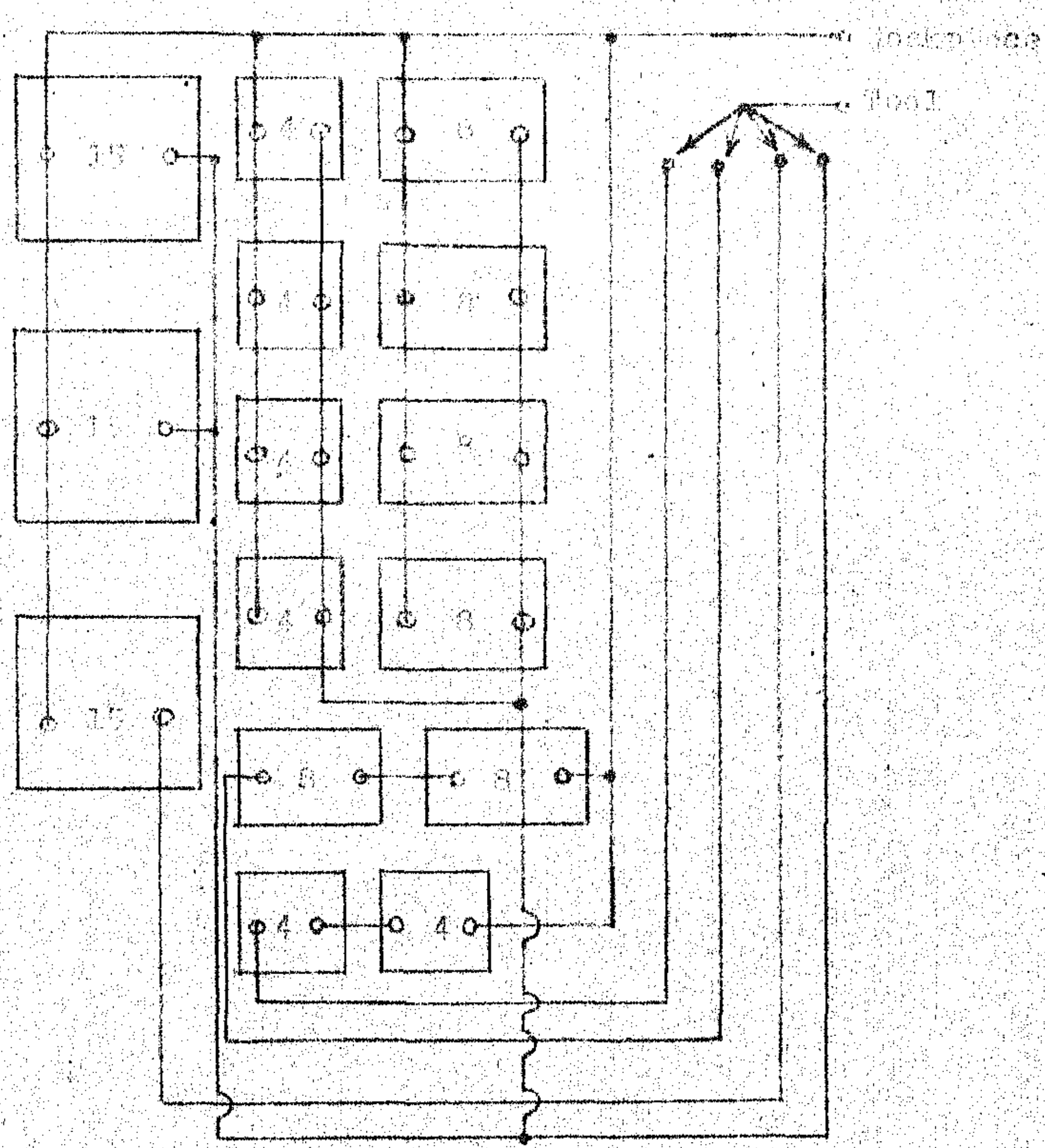
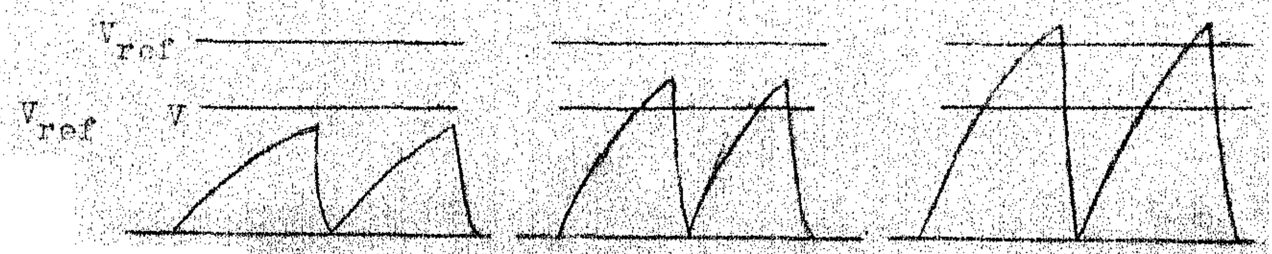


Fig. 4.3 Layout of Capacitance



Case I Case II Case III

Fig. 4.4 Possible Spark Waveforms

and be kept at a pre-set value. The whole tool control is based upon sensing this V_B and using it as a feed back signal to correct any error that has occurred during the machining process. In actual design, an upper and a lower limit have been fixed for this V_B beyond which correcting signal must go the stepper motor for its clockwise or counter clockwise movement thereby obtaining up or down motion of the tool. The Fig. 4.5 shows the logic flow chart for controlling gap width.

4.2.2 Hardware Details:

Based upon above principle, the circuit has been developed. Two comparators have been used, one compares V_B with V_{ref} set up by potentiometer and the other one compares V_B with $V_{ref} - \Delta V$. The outputs have been termed as V_1 and V_2 given by following logic equations:

$V_1 = 0$ or 1 accordingly as $V_{ref} > V_B$ or $V_{ref} < V_B$

$V_2 = 0$ or 1 accordingly as $V_{ref} - \Delta V < V_B$ or $V_{ref} - \Delta V > V_B$.

Referring to Fig. 4.4 , the comparator outputs can be termed as

Case I $V_1 = 0$, $V_2 = 1$ This corresponds to gap low hence tool must be raised

Case II $V_1 = 1$, $V_2 = 0$ This corresponds to gap correct hence no movement to tool.

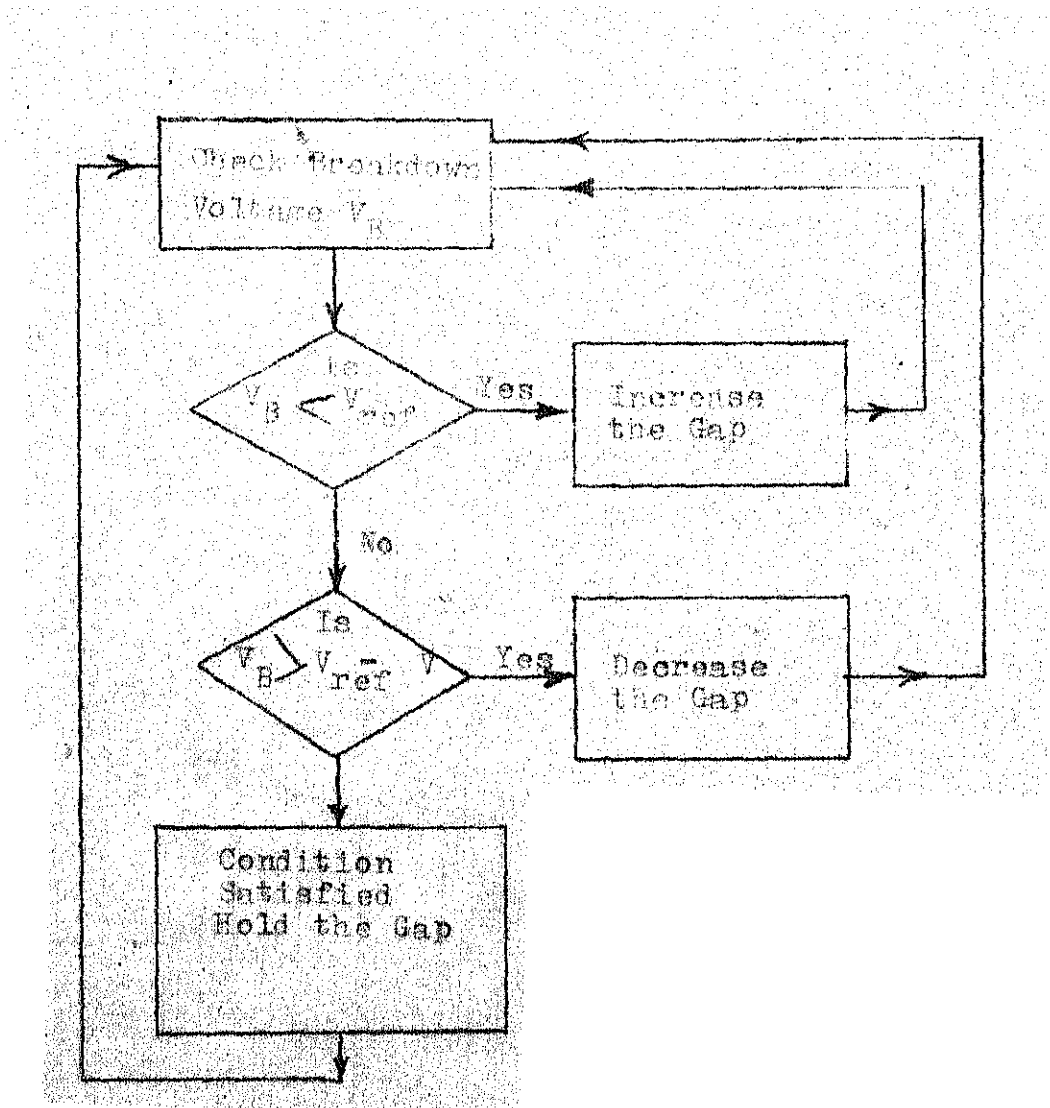


Fig. 4.5 Logic Flow Chart for Controlling the Gap Width

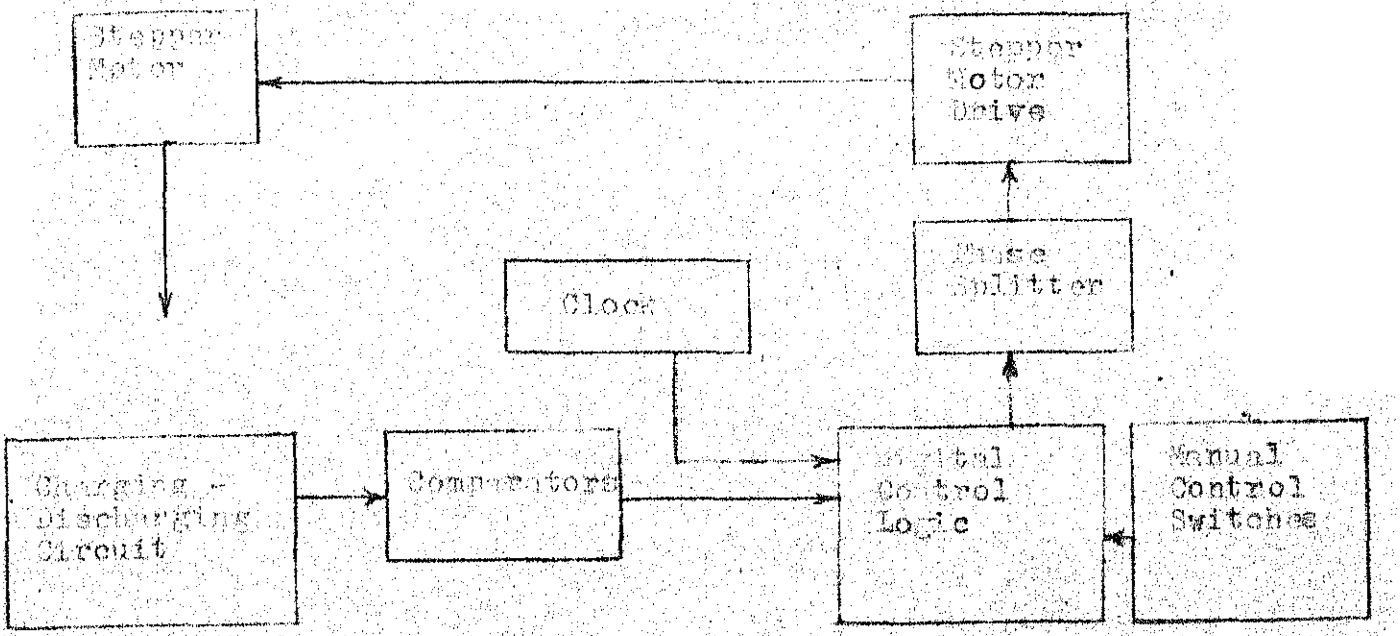


Fig. 4.6 System Block Diagram.

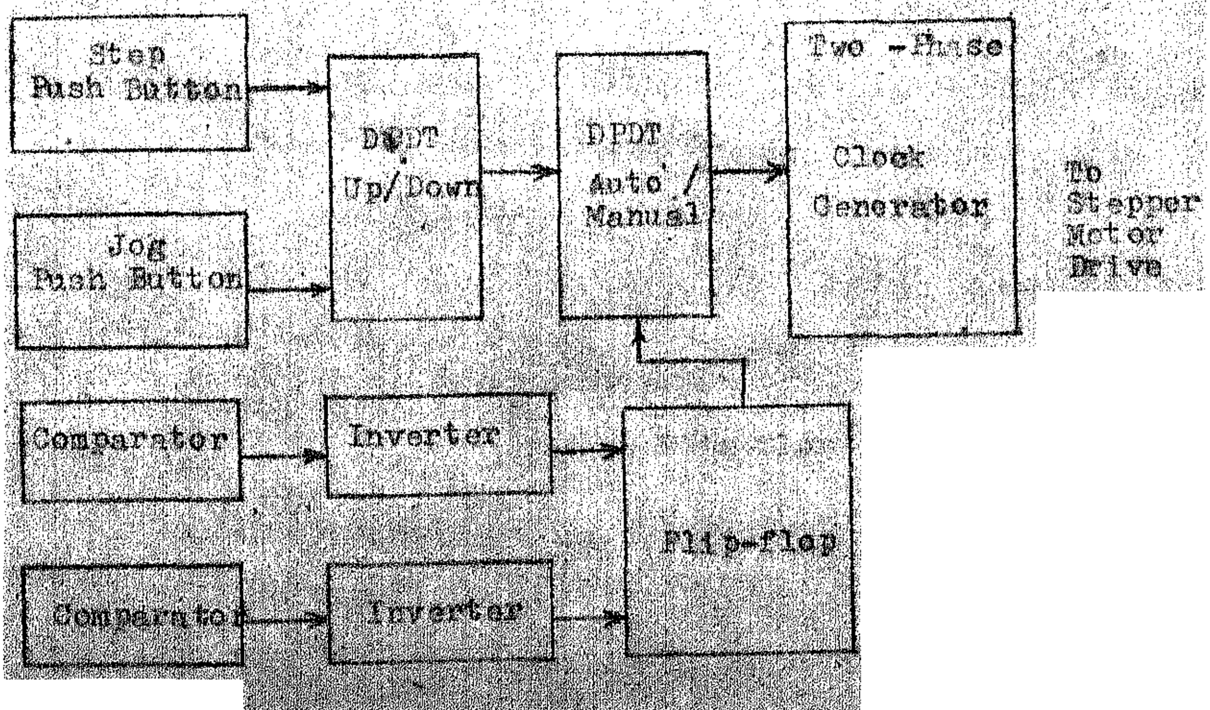


Fig. 4.7 Schematic Diagram of Control Logic

Case III $V_1 = 1$ This corresponds to gap high hence tool
$V_2 = 0$ must be lowered.

Thus these two comparators essentially determine whether the tool need be lowered, raised or should be held at that position. This output is fed to a sequential two-phase clock generator consisting of 7400 series TTL gates and flip flops to derive a proper sequence of energising the stepper motor coils and these output pulses are fed to the stepper motor drive circuitry for its clockwise or counter clockwise rotation.

The above procedure holds only for automode where V_1 and V_2 generated by the comparators are utilised to obtain pulses for the drive of the stepper motor. In manual mode, V_1 and V_2 are selected directly by the switches. The rest of the circuit and logic control is same as before. Since the whole system is digitally controlled and tool movement is by steps, a digital counter can be easily incorporated to indicate the tool position with respect to any preset reference level.

The block diagram of the whole EDM system has been shown in figure 4.6 and a schematic diagram of the control logic has been shown in Fig. 4.7, the detailed circuit diagram being given in Appendix D.

4.3 Special Features:

The following novel features have been incorporated in automade operation.

i) If the EDM switch is put off, V_B becomes zero and the tool starts moving upwards. The movement continues

until a microswitch becomes operative, activating a buzzer and informing the operator that tool need be lowered.

ii) In the extreme case of gap too low or short circuit condition V_B becomes zero there by comparator outputs becomes 0 and 1 which automatically send command to move tool up and correspondingly stepper motor rotates in clockwise direction till sparking initiates.

iii) In the event of the other extreme case, i.e. gap too wide, and no sparking occurs, V_B becomes equal to full supply voltage. Since V_{ref} is always set lower than the supply voltage, comparator outputs become 1 and 0 and signal to move the tool down is sent, and counter clockwise movement of stepper motor starts.

In manual operation, V_1 and V_2 are selected from the switch conditions and hence the operator has a choice of either moving the tool continuous in the desired direction (JOG) or moving in steps (STEP). Any desired gap width can thus be set by the operator.

The most important characteristics of the whole control system is that it has been achieved at a low cost with the help of indigeneously available 7400 series TTL gates and flipflops and 710 comparators. This has totally eliminated the complicated and costly electro-hydraulic servo system till now in use.

CHAPTER V

The machine with spark generation circuit and the tool control movement unit had been constructed keeping in view the design considerations mentioned in chapter III. Both spark generation circuitry and the digital feed-back control circuitry for the tool movement were housed in a separate box called the controller unit. The descriptions of the machine and the controller unit along with detailed specification of various equipments and parts are given in the following sections.

5.1 Machine:

The machine consists of the following major parts, i) structure and base, ii) Drive unit and feed mechanisms of the tool, iii) Working basin and its control, iv) Dielectric recirculation and filteration unit.

In Fig. 5.1, a schematic diagram of the whole machine is shown. The base of the machine is made of mildsteel plates welded together and bolted on wooden platform. A screw-jack of 6.35 mm pitch is fixed on this. A porcelin basin (45 cm x 30 cm x 15 cm) supported on mild steel frame is mounted on the screw-jack. In its lower most position, the base of the basin is at a height of 30 cm from the base level. By rotating the screw-jack, the basin can be fixed at any particular position within the two extreme positions of the travel of the screw-jack. This part is shown in Fig. 5.2.

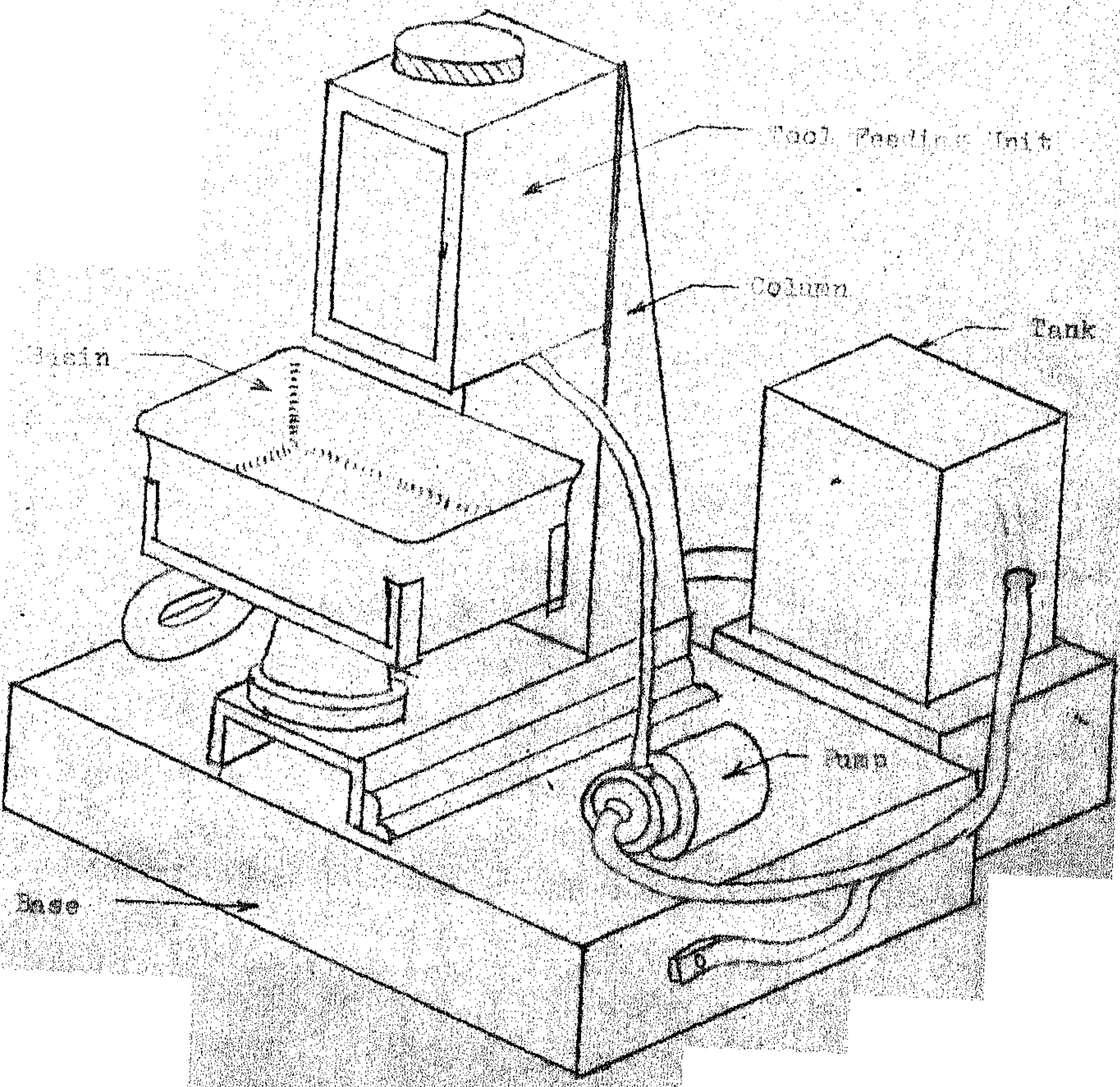


Fig. 5.1 Schematic Diagram of Machine

Fig. 5.3 shows the job holding device which is kept inside the basin and holds the job during machining process.

Fig. 5.4 shows schematically the tool feeding unit. The output shaft of the stepper motor is coupled to a lead screw of 3 mm pitch. A 12.7 mm thick perspex sheet is bolted to the lower portion of a moving slide which slides over a fixed dovetail guide. A tool holder shown in Fig. 5.5 goes inside a vertical hole of 3 mm dia, made in the perspex sheet, and is set by tightening a set screw. The tool is fitted in this tool holder. The total travel of the tool holder is 15 cm from its upper most position. The tool holder has the arrangement to receive the delivery side of the pump to facilitate the recirculation of dielectric fluid as well as the electrical connection necessary for the EDM process. The whole unit is fixed on the top portion of the column as shown in Fig. 5.1.

To maintain the recirculation of the dielectric fluid, a pump is fixed on the wooden base. The suction side is connected to a tank which stores the dielectric fluid. The delivery side is returned to the basin. The out let of the basin is connected to the tank completing the loop. The tank has also the arrangement for the drainage of the dielectric fluid.

5.2 Electrical Details:

Here the function of different switches and other instruments as shown in Fig. 5.6 and 5.7 are described.

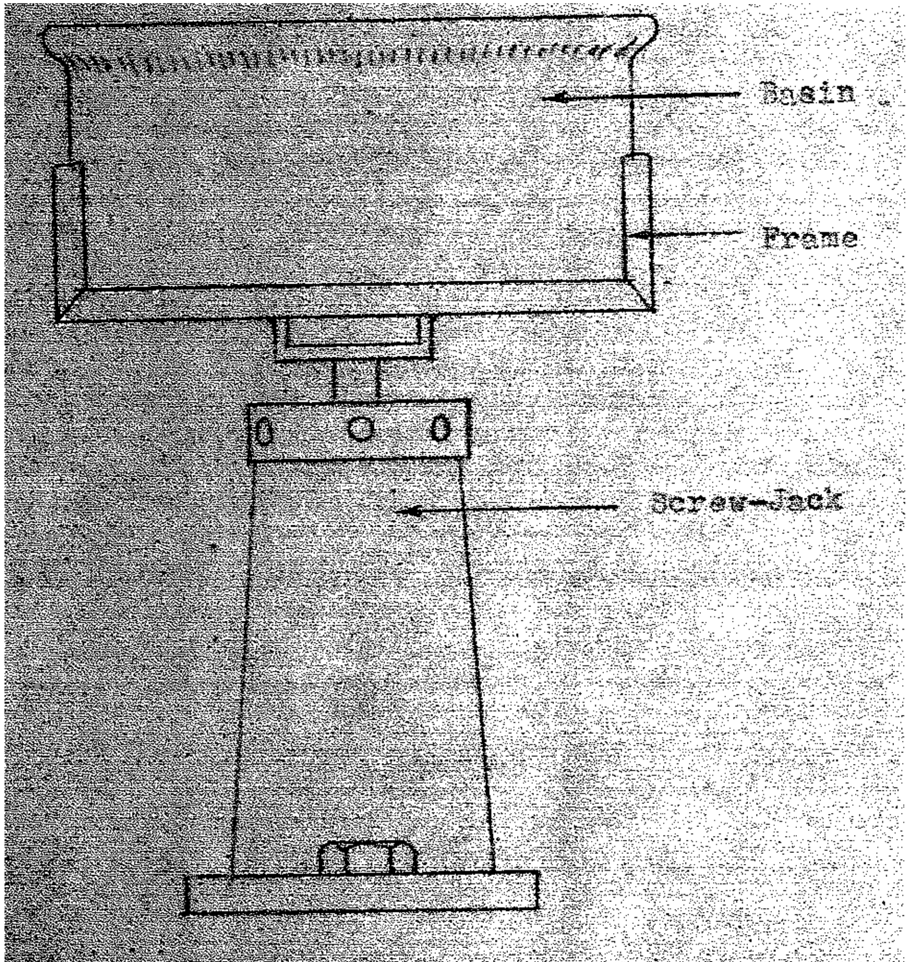
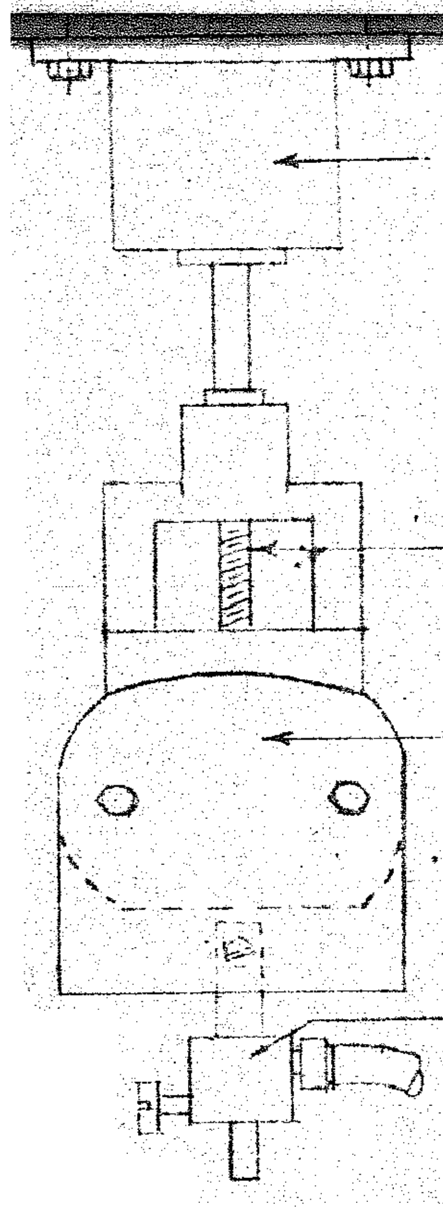


Fig. 5.2 Schematic Diagram of Basin



Schematic Diagram of Tool Feeding Unit

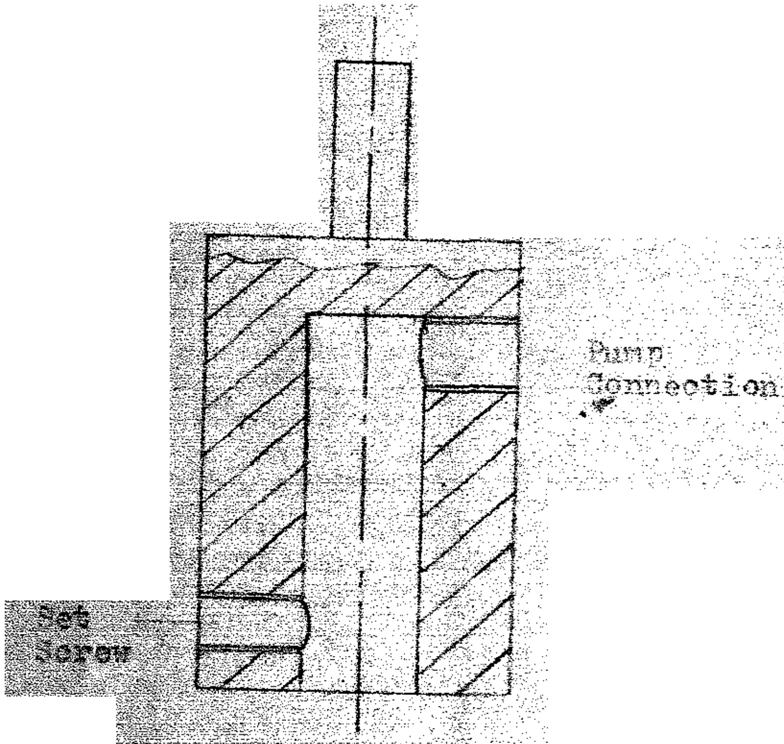


Fig. 5.5 Schematic Diagram
of
Tool Holder

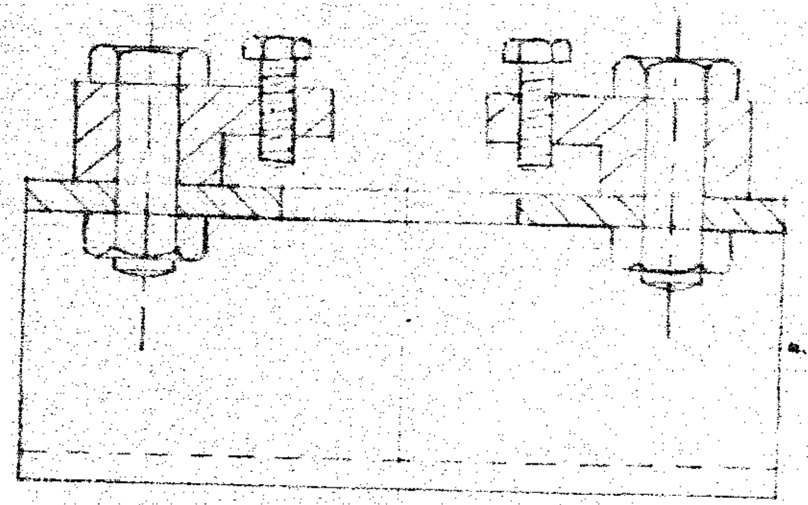


Fig. 5.3 Schematic Diagram
of
Job Holding Device

As mentioned earlier this can be divided into two catagories

i) Spark generating circuit control.

ii) Tool movement control.

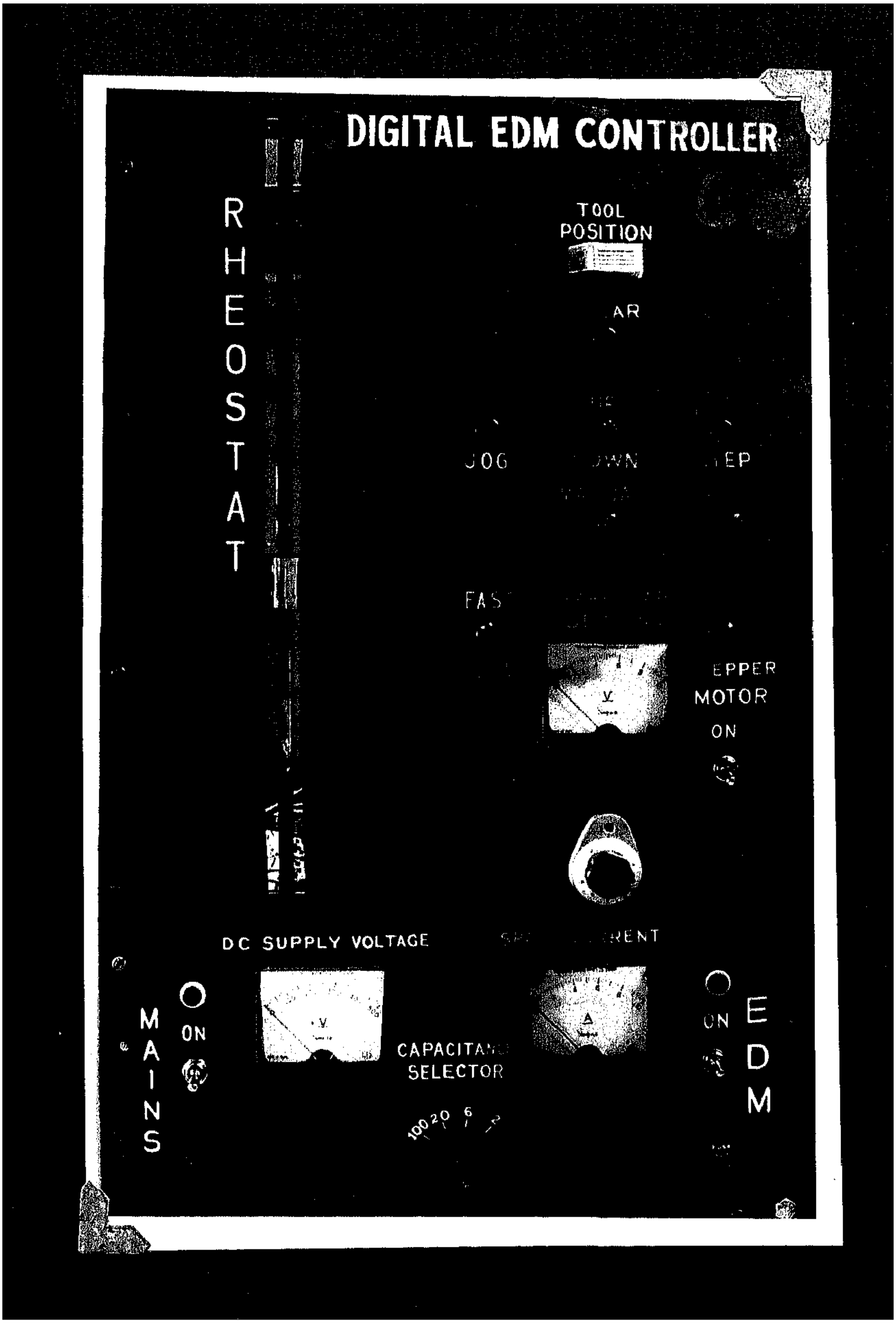
5.2.1 Spark generating Circuit Control:

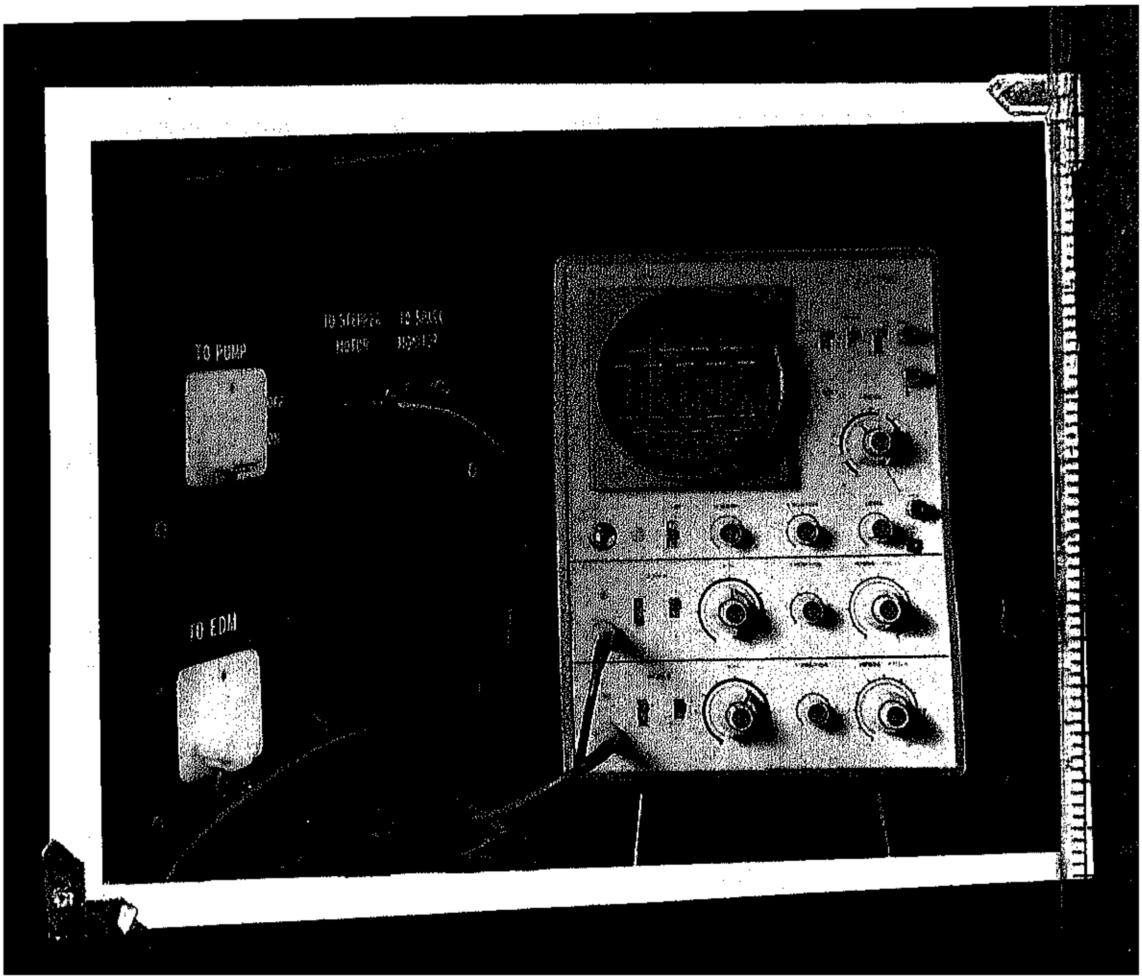
Fig. 5.6 shows the close up front view of the controller unit. Mains switch M, as the name indicates, allows the supply to various places. Through switch V placed on the left side, the supply is fed to a variac and its output is again taken in. This goes to a fullwave rectifier followed by a filter capacitor which smoothens the DC output of the rectifier. A DC voltmeter reads the DC voltage across this filter capacitor. The rheostat on the top left side is used for selecting the resistance, where as a 4 position capacitance selector switch selects one of the four capacitance values, 100 μfd, 20 μfd, 6 μfd or 2 μfd. The switch S on the right allows the power to EDM. Indicating lamp on the left denotes main power ''ON'' condition where as that on the right indicates ''ON'' condition of the machine. A DC ammeter on the right indicates the average value of the current during machining.

5.2.2 Tool Movement Control:

This is essentially a digital electronic control as explained in the earlier chapter. The functions of the different switches, shown in Fig. 5.6, are explained below

On the top, under Tool Position, there is a provision to fix a 4 digit 7 segment L.E.D. display which will show


DIGITAL EDM CONTROLLER
TOOL POSITION
RHEOSTAT
MOTOR
ON
DC SUPPLY VOLTAGE
MAINS
ON
SELECTOR
ON
EDM


TO PUMP
TO EDM

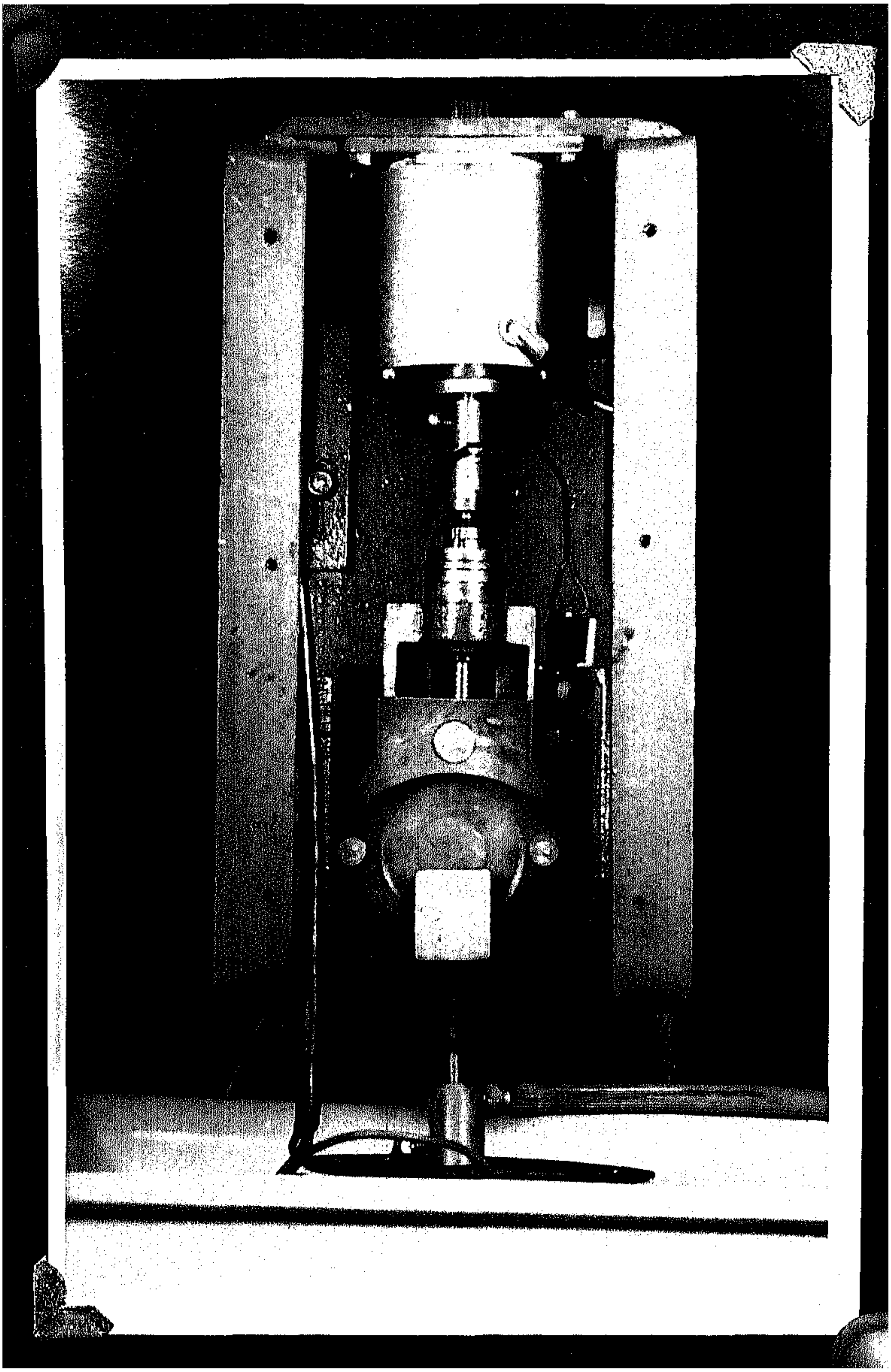
the down ward tool movement from any preset value. A push button switch ''P_1'' just below it clears all of them when pressed. The toggle switch ''A'' below it selects up or down condition for manual mode as indicated. Push button switch ''P_2'' just left of it allows jog motion so long it is kept pressed. Push button switch ''P_3'' on the right of Up - Down switch allows movement of the tool by a single step.

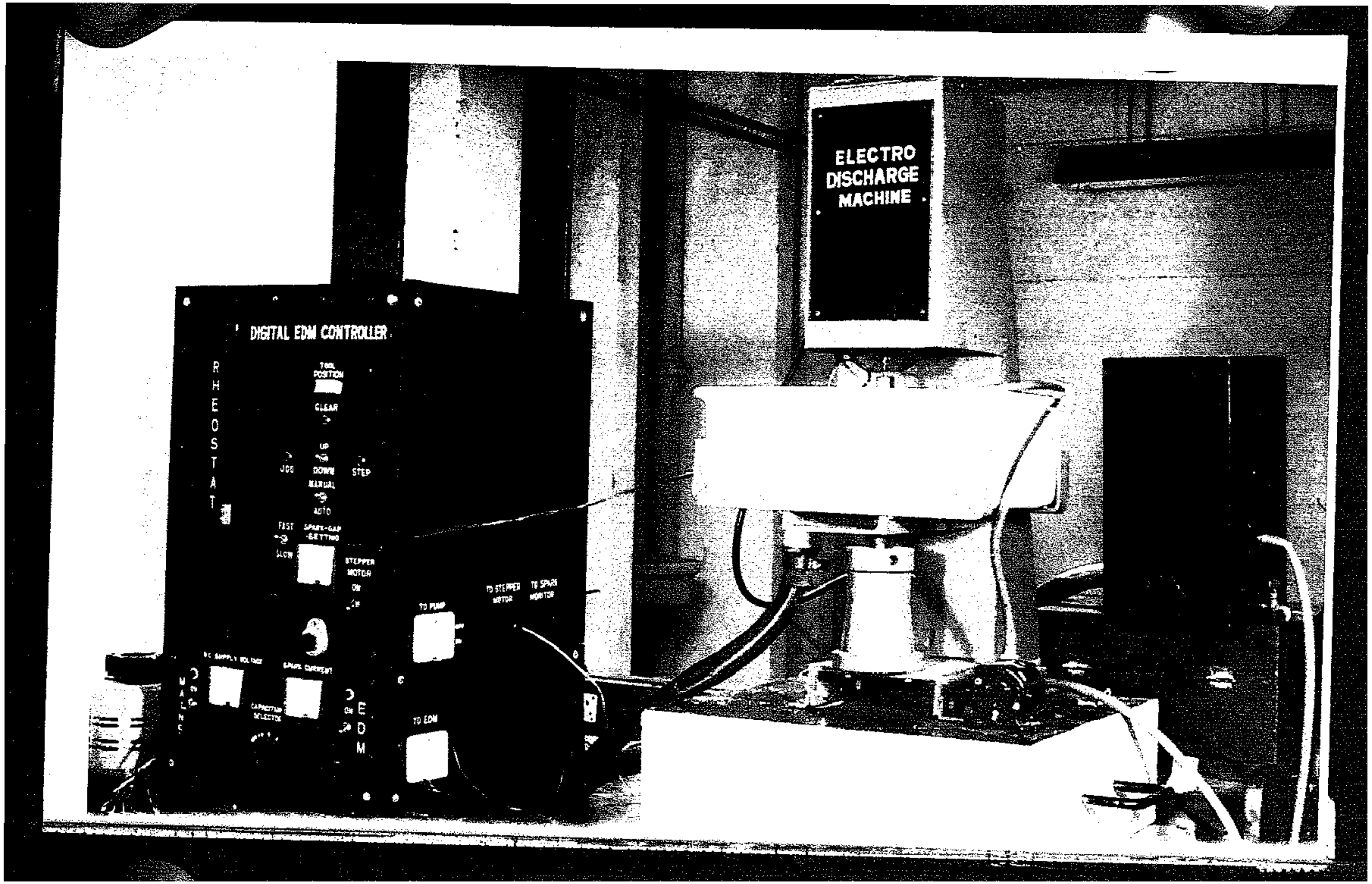
The toggle switch ''B'' below the Up down switch ''A'' selects the manual or automode operation. The switches A, P_2 and P_3 are operative only when switch ''B'' is in manual mode. Since auto mode operation override the manual operation the switches A, P_2 and P_3 becomes inoperative during automatic operation.

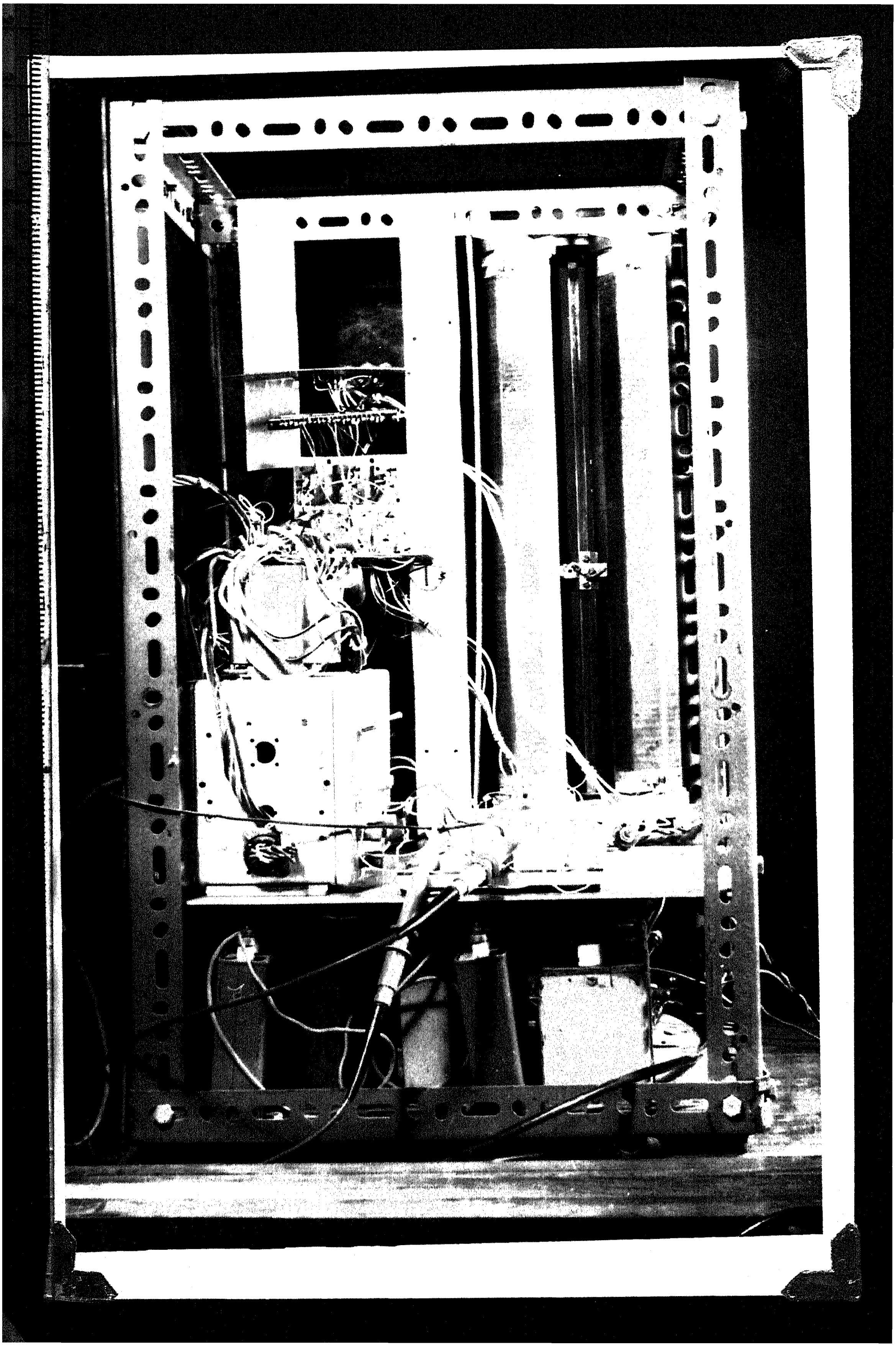
The potentiometer sets V_{ref} or the upper limit of the break down voltage V_B, which indirectly denotes the gap as explained in the earlier chapter . The DC voltmeter indicates V_{ref} modified by a scale factor of 47.

The toggle switch ''C' on the top left corner of the voltmeter selects fast or slow rotational speeds. The toggle switch ''D'' on the bottom right of the voltmeter is for stepper motor power supply. The green indicating lamp just above it depicts stepper motor ''On'' condition.

On the right side panel there is switch and socket arrangement for the supply of power to the pump. The next socket is for the power to stepper motor. There are two connections marked as Spark Monitor which can be connected to




ELECTRO
DISCHARGE
MACHINE
DIGITAL EDM CONTROLLER
RHEOSTAT
TOOL POSITION
CLEAR
UP
DOWN
JOG
STEP
MANUAL
AUTO
FAST
SLOW
SPARK-GAP SETTING
STEPPER MOTOR
TO PUMP
TO STEPPER MOTOR
TO SPARK MONITOR
DC SUPPLY VOLTAGE
SPARK CURRENT
CAPACITANCE SELECTOR
MAINS
EDM
TO EDM



H)	Stepper motor	12V, 1.2Amp, 10 Kg.cm torque step-syn Reversible Step motor
I)	Power supply	Input: 230V 50 c/s A.C. Output: $\pm$ 12V, $\pm$ 5V, $\pm$ 7-25V,1Amp
J)	Microswitch	1NC 1 NO 5 Amp 230V
K)	Buzzer	230V AC/DC
L)	Sparkgap setting Voltmeter:	0-10V Moving coil type
M)	Potentiometer	5 Kilo ohm, Lin 15 % Tolerance 1 % , type 2.5Y10
N)	UP-DOWN and AUTO-MANUAL Switch:	Double pole-double throw 2 Amp.
O)	Pump	Tullu Make 0.025HP 40 watt cont. Head=4.6m capacity = 136 LPH AC/DC 230V.
P)	Dielectric fluid:	Kerosene.

CHAPTER VI

RESULTS AND CONCLUSION

All the experiments were carried out for an identical combination of tool and workpiece material : tool being brass and job being mild steel.

6.1 Measurement of frequency:

Frequency of sparking was measured by a digital frequency counter in both manual and automode for different values of C and V_s under ''Constant Short-circuit current'' condition. Fig. 6.1 shows variation of the frequency of sparking with time for a steady tool position.

It is observed that frequency of sparking gradually decreases with increase in time as expected because the gap width increases due to metal removal from the workpiece and the tool. Since there is no feed of the tool correspondingly, V_B increases resulting in lower frequency of sparking.

It should be noted that starting frequency values for different capacitor for a particular V_s do not necessarily correspond to the same gap width although they start from the same point on the graph, since there is no way to measure and set the actual gap width, at the time of starting each experimental run.

In the automode the values of frequency have been shown in Table 6.1. The values are highly erratic in nature

and no useful quantitative conclusion can be drawn from them. This is because the peaks of the spark waveform do not stabilise between the band V_{ref} and $V_{ref} - \Delta V$ as theoretically expected. On the other hand, the peaks randomly fluctuate between complete short circuit condition to nearly open circuit condition. This has also been observed in the CRO display of the spark voltage waveform.

One possible explanation could be the somewhat high pitch of the Lead screw. Since the control is digital, and causes tool motion in discrete steps, the minimum correction of the tool position is about 18μ and causes overshoots and undershoots on both sides of the desired gap setting to the extent of creating open-circuit and short-circuit condition respectively. Oscillations of the tool movement are therefore expected and this hunting has indeed been observed during experiments. To reduce this hunting, different types of control circuits were designed and implemented, with little avail, indicating that this hunting is, to a large extent, inverent in this system.

In spite of the erratic variations in the frequency of sparking, a general trend of rise in frequency with decrease in capacitance is discrenible. But this rise appears to be less than the theoretical inverse dependence on C would require. This also is likely to be a consequence of the hunting of the tool control, since as pointed out, that

the peaks of the spark voltage waveform are considerably higher than the gap setting demanded by V_{ref}.

6.2 Measurement of MRR and EWR

Metal removal rate and Electrode wear rate were calculated in automode for different values of V_s and C under ''Constant short-circuit current'' condition. In each case V_{ref} had been set at a value approximately equal to the theoretical optimum i.e. for $V_B = 0.7V_s$. The variation of MRR and EWR for different values of V_s and C have been shown in Figs 6.2 and 6.3. The curves show a nearly consistent increase in MRR with increasing values of V_s for same capacitance.

For the same V_s increase in C is found to lead to an increase in MRR . This contradicts the theory , and is a consequence of the observation already made in the proceding section that the frequency does not vary inversely with capacitance the peak value of the spark waveform being equal to V_s most of the time. This is also the reason for the low value of MRR obtained from the experiments.

Comparison of MRR obtained with certain existing models show that the highest MRR recorded with the present system is about 20 times less. However, the commercial machines have current handling capacity of the order of 30-40 amps. Due to electrical equipment limitation this machine had to be operated at a short circuit current of 4 amp. Since MRR is directly proportional to current, a

ten fold increase in current would have multiplied the value of MRR ten times. Moreover, the supply voltage can be further increased, which would also result in higher MRR. Apart from the above observations, study of surface finish of workpiece was also carried out. No quantitative measurements could be made, only qualitative inferences could be drawn . It was observed that the combination of lower supply voltage and capacitance caused better surface finish than higher voltage and capacitance. However, it had been seen that change in value of capacitance has more effect than supply voltage.

6.3 Scope for Future Work:

Work can be carried out in the further development of the machine, making it more sophisticated in the form of 3 axis tool movement, angular feed etc. Experiments can be carried out for different tool-job combinations and optimum values of different electrical parameters can be found out experimentally for maximum MRR and minimum EWR for its better commercial utilisation.

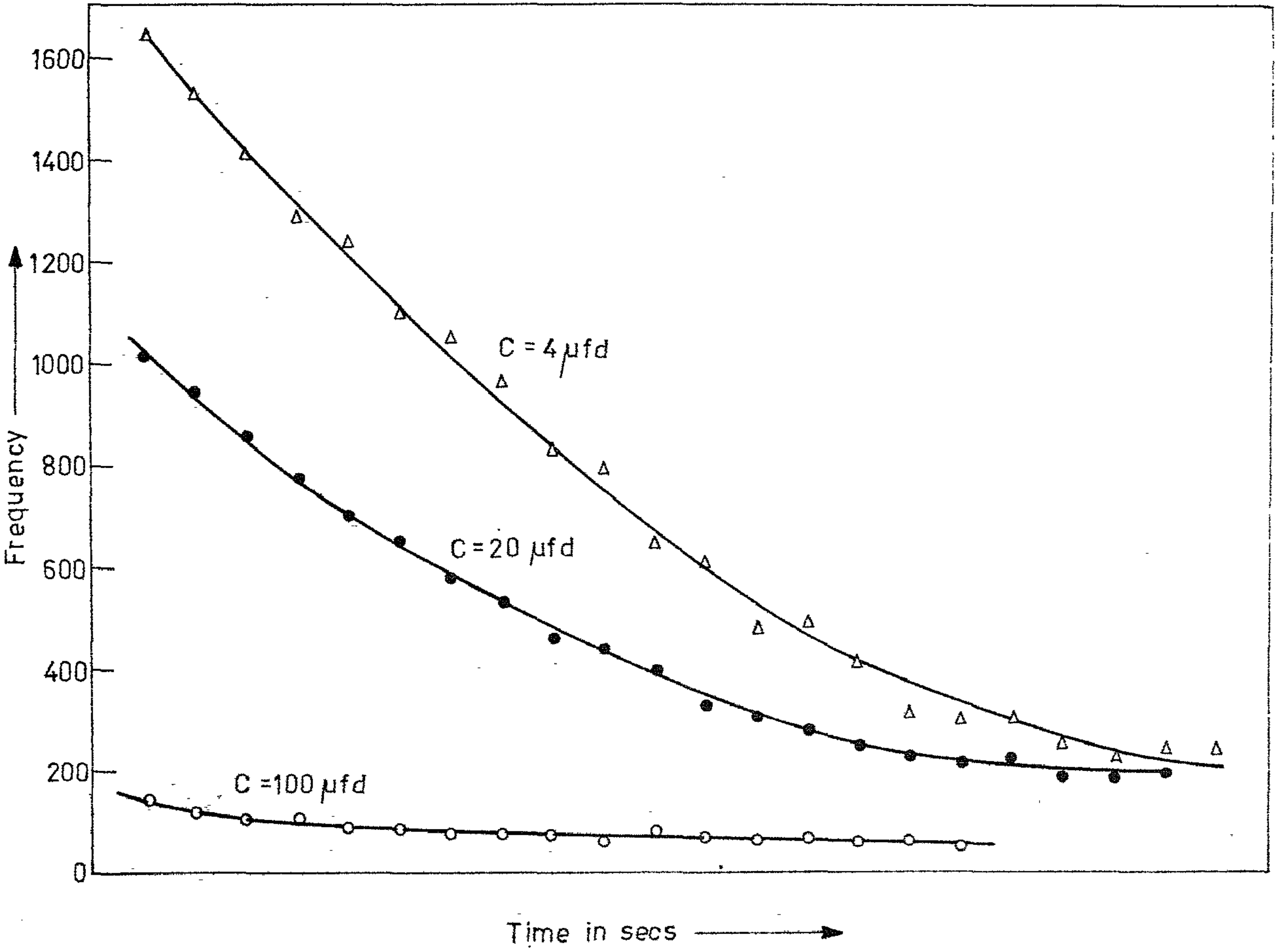


Fig. 6.1a. Frequency of sparking vs time (V_S=100 Volts)

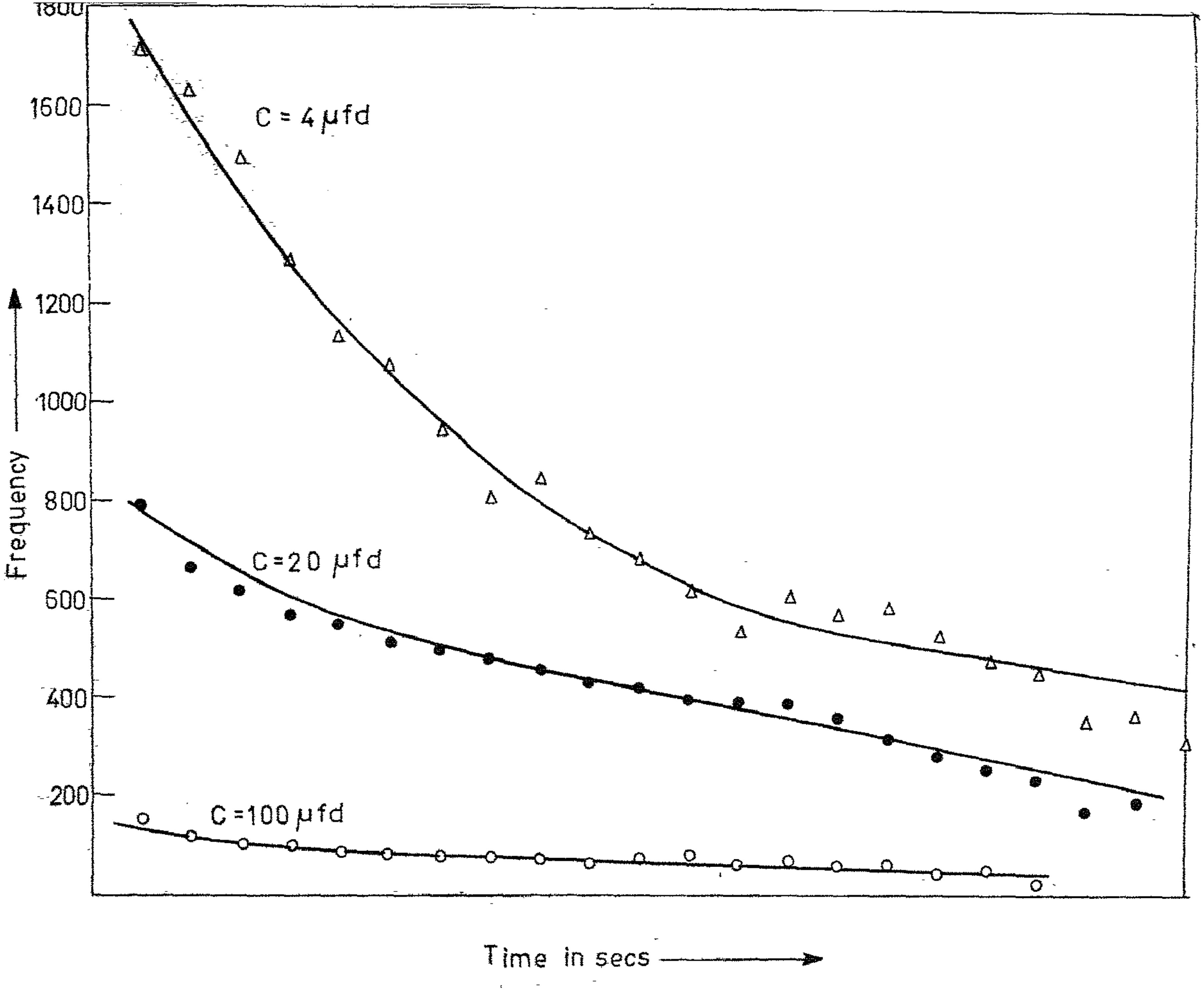
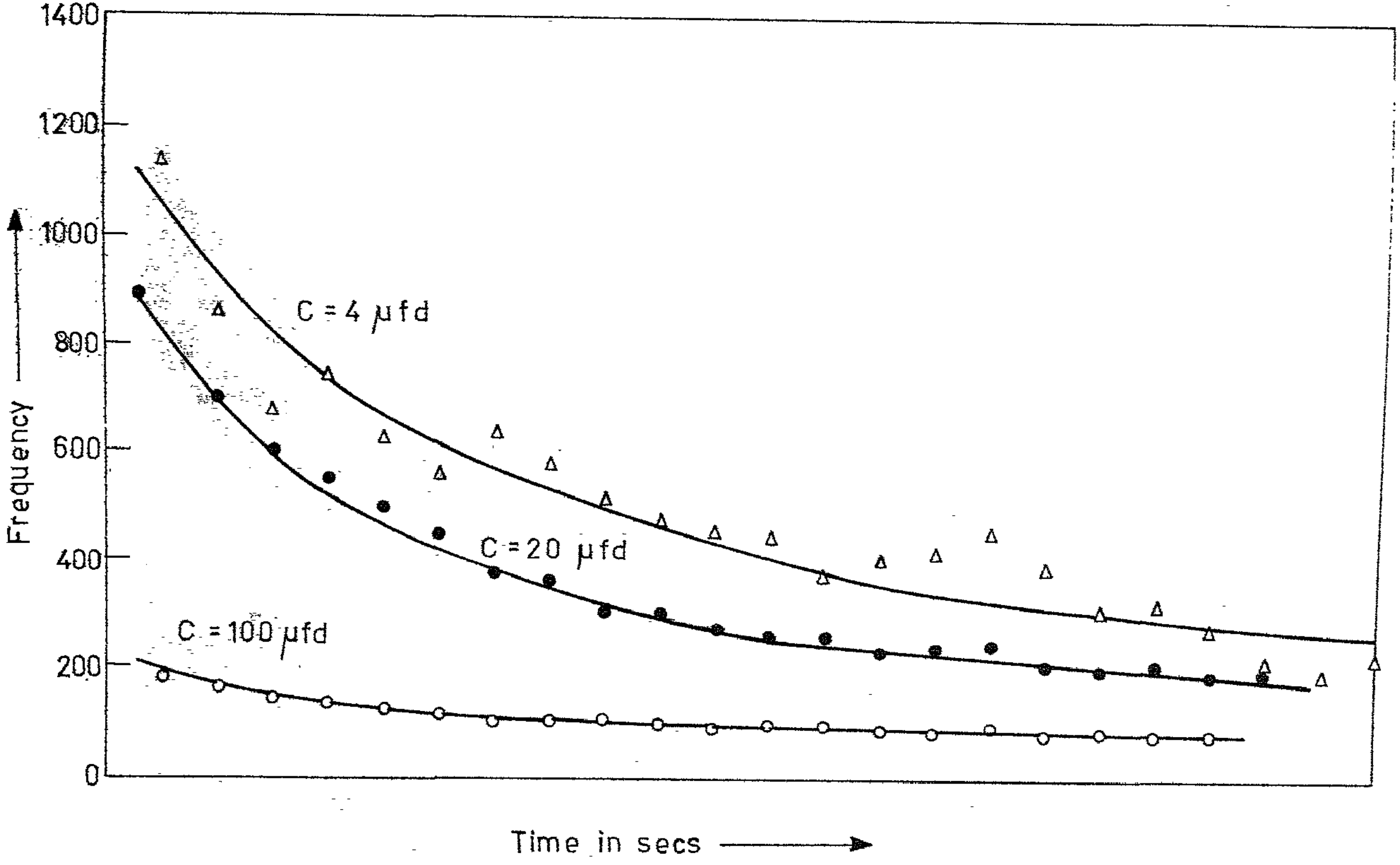


Fig.6.1b Frequency of sparking vs time (V_s = 150 Volts)



Eig. 6.1c Frequency of sparking vs time (V_S = 200 Volts)

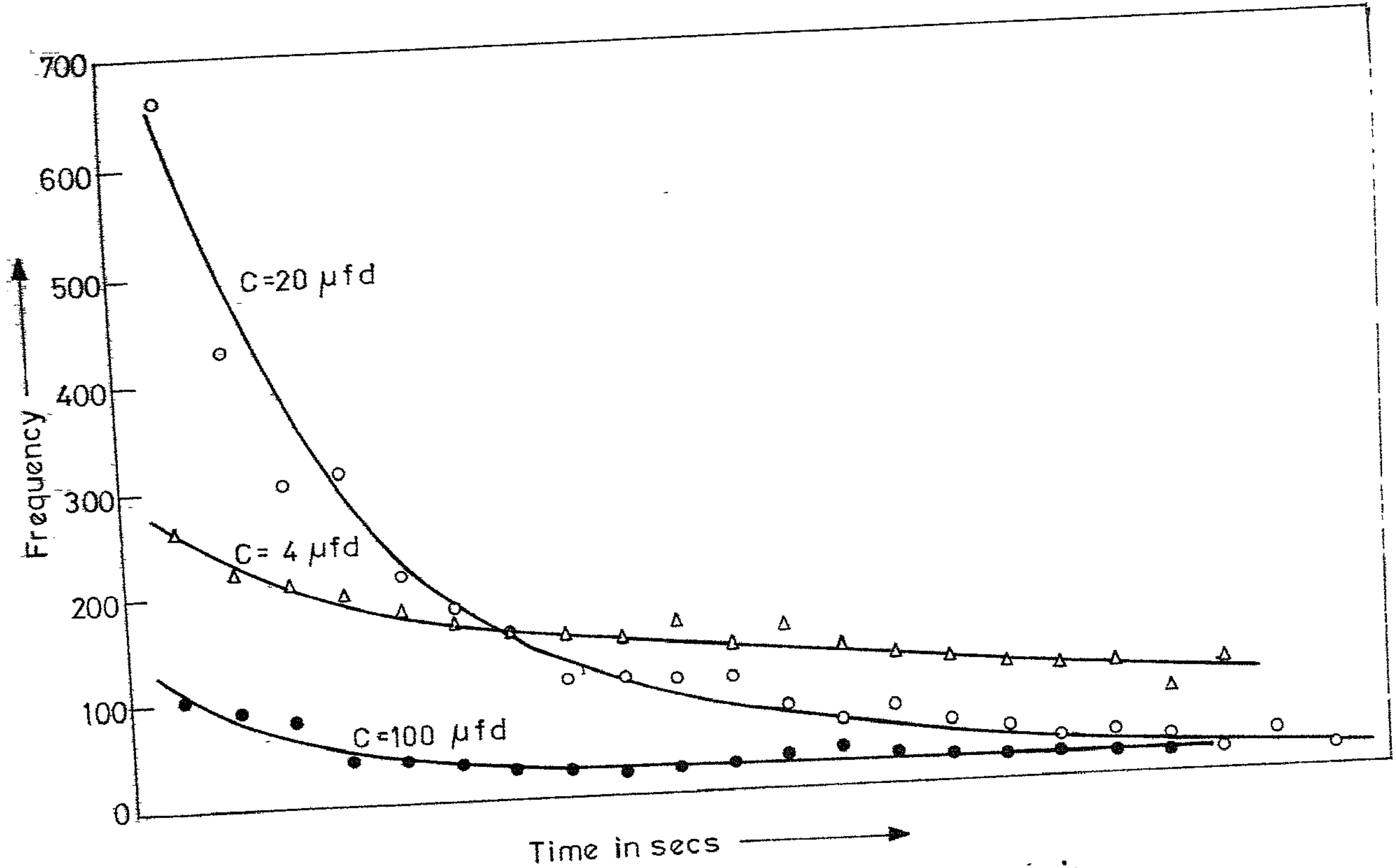


Fig 6 1d Frequency of sparking vs time (V_s = 250 Volts)

TABLE 6.1 (continued)

V_s = 150 Volts

C = 100µfd				C= 20 µfd				C = 4 µfd			
120	148	162	152	714	694	860	416	1599	1351	1564	1360
169	124	137	111	448	628	510	682	1107	1682	1338	1108
122	113	87	122	516	984	435	445	1217	1233	1344	1061
143	177	140	177	567	548	832	1097	1064	1157	1623	821
173	118	161	141	590	838	663	727	551	757	642	641
151	140	108	134	645	620	767	614	711	1113	889	854
114	116	176	148	495	784	437	591	654	396	395	192
119	129	128	123	726	596	462	482	188	412	1054	916
121	164	136	99	689	465	497	379	877	1121	722	735
109	129	90	153	508	397	302	737	1213	1316	225	405

V_s = 100 Volts

C = 100 µfd				C = 20 µfd				C=4 µfd			
246	186	200	154	560	[illegible]	442	485	1508	1338	1357	1322
197	185	191	198	508	590	569	514	1314	947	1528	1626
186	148	144	148	630	414	418	399	1352	1318	1518	1508
149	169	158	162	498	495	455	532	1969	2197	1877	1300
163	184	194	112	791	555	530	879	1594	1572	1075	607
180	182	154	191	633	672	637	602	1173	1186	1342	1485
190	167	168	270	675	565	559	503	1576	1204	1450	1247
238	208	200	229	679	529	765	644	1085	1034	1225	1417
244	165	236	198	550	523	463	519	1775	1971	1291	922
182	196	202	246	598	456	403	503	1385	1979	1449	1930

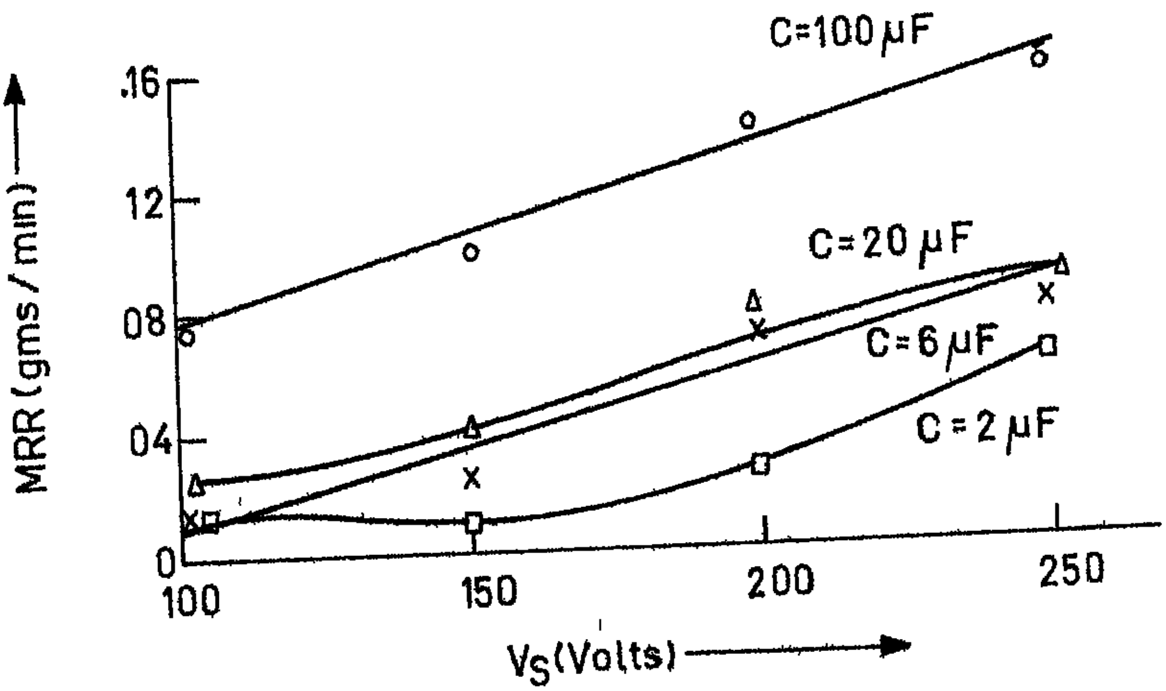


Fig 6 2 Variation of MRR with supply voltage

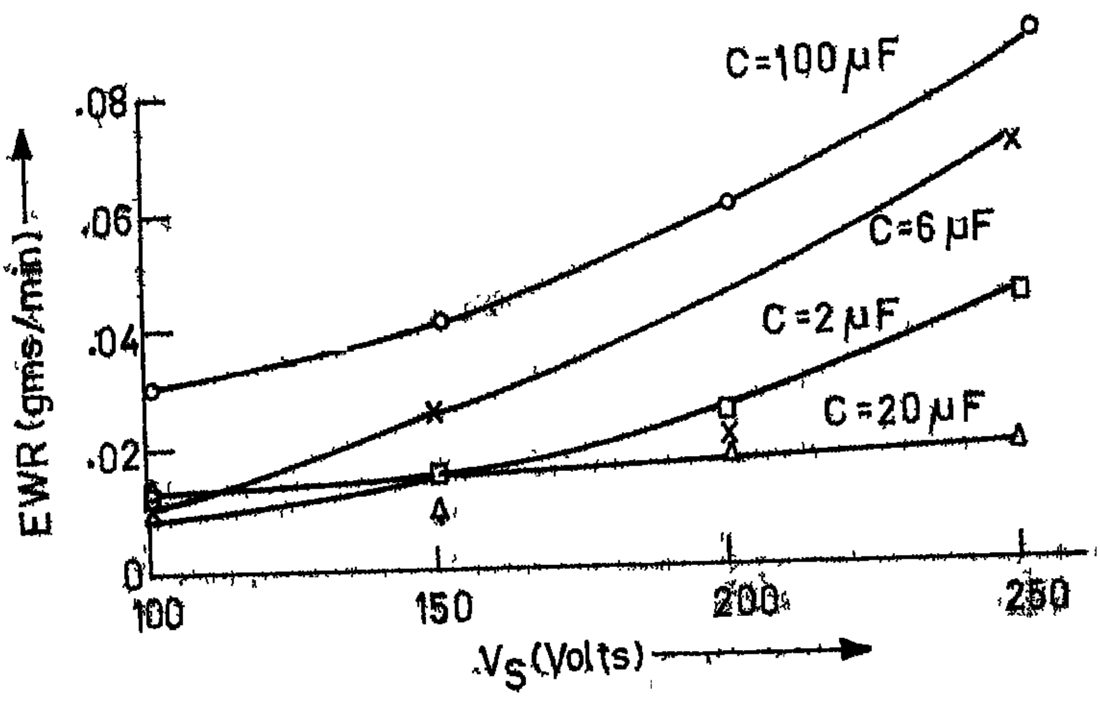


Fig 6 3 Variation of EWR with supply voltage

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APPENDIX A

For the i^{th} spark equation 2.1 can be written as

$$V_{B_i} = V_s \left(1 - e^{-\frac{T_i}{RC}} \right)$$

Squaring both sides

$$V_{B_i}^2 = V_s^2 \left(1 - e^{-\frac{T_i}{RC}} \right)^2$$

For m consequtive sparks it reduces to

$$\sum_{i=1}^{m} V_{B_i}^2 = V_s^2 \sum_{i=1}^{m} \left(1 - 2e^{-\frac{T_i}{RC}} + e^{-\frac{2T_i}{RC}} \right)$$

For small values of m, it can be assumed that m spark occurs in time ΔT and summation sign can be replaced by integration sign.

So $$\sum_{i=1}^{m} V_{B_i}^2 = V_s^2 \Delta T - 2 V_s^2 \int_{T}^{T+\Delta T} e^{-\frac{T_i}{RC}} dT + V_s^2 \int_{T}^{T+\Delta T} e^{-\frac{2T_i}{RC}} dT$$

Since ΔT is very small, considering first order terms only

$$\sum_{i=1}^{m} V_{B_i}^2 = V_s^2 \Delta T \left[1 - 2 e^{-\frac{T}{RC}} + e^{-\frac{2T}{RC}} \right]$$

or $$\frac{1}{m} \sum_{i=1}^{m} V_{B_i}^2 = V_B^2 = V_S^2 \left(1 - e^{-T/RC} \right)^2$$

or $$V_B = V_s \left(1 - e^{-T/RC} \right)$$

APPENDIX B

The theory of operation of a stepping motor is based on the theory of operation of a synchronous inductor motor. In a synchronous inductor motor, torque is developed as a result of the interaction of an alternating magnetic field, produced by a stationary multiphase winding and on unidirectional flux. This type of motor is characterised by numerous toothed projections on stator and as well as on rotor. If the rotor teeth are at a pitch where it has one more tooth then the stator for each four poles of the stator, assuming a two phase winding there on, then the rotor will advance one tooth pitch for each complete cycle of the applied frequency. Therefore the rotor speed is given by.

$S = \frac{60}{n}$ f where,

S = rotor speed in rpm.

f = frequency in cycles per seconds

n = the number of teeth on the rotor

The above theory is applicable to the stepping motor. The stator has a two phase four pole winding with a total of eight poles and the rotor punchings have fifty teeth. In order to make an efficient magnetic structure, the rotor is made with two separate indentical disks, separated by a cylindrical permanent magnet, which is magnetised axielly making one rotor section a north pole and the other a south pole . To preserve the proper magnetic relationship, the teeth of the two sections

are off set by one half a rotor tooth pitch. This arrangement permits the use of a common stator magnetic structure and winding. The torque due to the two sections of the rotor add directly.

The flux starts from the north pole of the magnet, travels radially outward through one section of the stator along the outer shell and returns through the other half of the structure. It is evident that the fluxes combine and hence interact in the air gap. In the rotor sections and in the back section of the stator laminations,the two fluxes are at right angles. Since the alternating flux does not flow through the permanent magnet there is obviously no tendency toward demagnetisation. It is clear that,if two phase power is applied to the windings, the rotating magnetic field will cause a mechanical advancement of one rotor tooth pitch or 36 degrees for every 360 electrical degrees.

The above operation is extended by replacing each half cycle of the sine waves with a square wave,representing a train of d.c. pulses of two polarities, to get stepped d.c. operation. The motor used in this case has bifiliar windings. So, instead of reversing the current in a winding, current of the same polarity is switched to an identical winding wound in the opposite direction. Between each switching operation,d.c. passes through the stator coils and supplies a holding torque that holds the rotor in the position to which it had been moved by the preceeding switching operation.

When the current is reversed in one of the windings, the rotor is turned through an angle of 1.8 degrees.

To achieve such switching operations, the stator windings must be energised as shown in table No. 6.1.

TABLE NO. 6.1

Step	State of Winding			
	A C.W.	A' C.C.W.	B C.W.	B' C.C.W.
1	0	0	0	0
2	1	0	0	1
3	1	1	1	1
4	0	1	1	0

APPENDIX C

CALCULATION OF PIPE DIAMETER

For smooth running of the machining process it is desirable to have a steady level of the dielectric medium in the working basin. Since it is impossible to maintain absolutely steady level in the basin because of constant inflow and outflow of the dielectric fluid from it the maximum allowable fluctuation in the level of the basin is restricted to 0.1 cm.

Capacity of pump = 136 lits/hour = 37.8 cm^3/sec

Area of basin = 45 cm x 30 cm

Area of tank = 25 cm x 15 cm

Let corresponding change in tank level = h cm

Therefore $45 \times 30 \times 0.1 = 25 \times 15 \times h$ or h = 0.36cm

Thus head causing flow from basin to tank = 0.46 cm .

This flow must balance the discharge from the pump to the basin.

Equating two flows,

$$Q = 37.8 = \sqrt{2 \times g \times 0.46} \times \pi/4 \times D^2$$ where D=Dia of pipe in cm

Solving D = 1.27 cm

In actual practice the net head causing flow would be very much less because there will be friction drop in the pipe line due to clogging and settling of the erosion products. Thus to remain on the safe side a pipe diameter of 3 cm has been chosen.

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